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SPATIOTEMPORAL CHARACTERISTICS OF VISUAL LOCALIZATION

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University of North Carolina

SRI Project 6616

Prepared for:

Air Force Office of Scientific Research
Building 410
Bolling Air Force Base
Washington, DC 20332-6448

Attn: Dr. John Tangney
Scientific Program Officer

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CONTENTS

I INTRODUCTION i

II RESEARCH PROGRESS 3

- A. Completed Papers, Their Relation to the Driving Questions, and New Directions 3
- B. Comparison of Orientation and Separation Discrimination Using Two Experimental Paradigms 10
- C. Context Effects in Separation Discrimination: Spatial-Frequency Independence 11
  1. Equating Effective Contrast across Spatial Frequency and Exposure Duration 12
  2. Effects of Spatial Frequency and Exposure Duration on Separation Discrimination Thresholds with Embedded Targets 12
  3. Diffusion Screen Results 13
  4. Interobserver Differences 16
  5. Conclusions 16
- D. Perceived Spatial Frequency and Spatial-Frequency Discrimination Thresholds 17

III PUBLICATIONS, PRESENTATIONS, AND OTHER 21

- A. Written Publications 21
- B. Oral Presentations 21
- C. Consultative and Advisory Functions 22

REFERENCES 25

APPENDICES

- A. Two Mechanisms for Localization? Evidence for Separation-Dependent and Separation-Independent Processing of Position Information 29
- B. Spatial Contrast Integration and the Length Effect in Separation Discrimination 41
- C. Spatial-Filter Selection in Large-Scale Spatial-Interval Discrimination 77
- D. Spatiotemporal Limitations in Bisection and Separation Discrimination 89
- E. Spatial Interactions in Rapid Pattern Discrimination 137

ILLUSTRATIONS

Figure 1	Shift in perceived separation caused by the presence of a third line. Mean separation to be judged was 0.75°. The abscissa is the mean distance between one of the target lines and the third (extraneous) line. Data are shown for two durations and two observers	8
Figure 2	Contrast sensitivity for two observers for target lines presented approximately 1.5 degrees in the periphery. Data are shown for two exposure durations	13
Figure 3	Separation discrimination thresholds for targets embedded in an array of four parallel flanking bars as a function of the spatial frequency of the targets and flanking bars (always equal). Data are shown for two durations for each of two observers	14
Figure 4	Separation discrimination thresholds for a pair of target bars measured as a function of the blur of the individual bars. Data are shown for two observers and two durations at two separations. The change from circular to square symbols indicates a change in viewing distance	15
Figure 5	Change in spatial-frequency discrimination thresholds following adaptation to a high-contrast grating. The filled circles are data obtained for two observers in our laboratory. The open circles are from Figure 1 of Regan and Beverly (1983)	18
Figure 6	The change in spatial-frequency discrimination thresholds following adaptation to a high-contrast grating predicted by the perceived spatial-frequency shift (obtained in simultaneous measurements for each observer), shown by the filled symbols. Also shown for comparison are the data actually obtained, shown by the open symbols. Data are shown for two observers	19

I INTRODUCTION

In the original statement of work for this project, we proposed to conduct experimental psychophysical research, together with the necessary and appropriate theoretical development, on three topics:

(1) Test and explore the theory that spatial-interval discrimination thresholds can be determined at any of several stages of processing, the precise stage depending on the details of the stimulus. Specifically, we will seek those conditions that cannot be accounted for by linear spatial filters.

(2) Explore the source of the exposure duration effect in localization judgments, by investigating its dependence on both the spatial frequency content and retinal eccentricity of the stimulus, and by relating these results to properties of the spatial filters as revealed in analogous contrast-detection experiments.

(3) Investigate the spatial characteristics of the receptive fields underlying the proximal localization mechanisms and relate them to those of linear spatial filters.

II RESEARCH PROGRESS

A. COMPLETED PAPERS, THEIR RELATION TO THE DRIVING QUESTIONS, AND NEW DIRECTIONS

Our research in recent years has focused on moving up a theoretical visual pathway, identifying and isolating the components involved in the extraction of spatial structure from a visual scene. Our main paradigm has been separation discrimination, *i.e.*, the judgment of the distance between objects in a fronto-parallel plane. To identify the properties of the mechanisms that actually encode the separation between objects, we adopted a bottom-up approach. Under previous AFOSR sponsorship, we showed that the local spatial filters that had been postulated to account for some contrast detection results—and were being used to model relative position data (Wilson and Gelb, 1984)—were fundamentally insufficient to account for the general phenomenon. The spatial-filter model asserted that both targets were detected by a single filter, which signaled their separation directly. Although this model provides a natural means of accounting for the increase in separation discrimination thresholds with increasing separation, it is readily refuted by looking at larger separations and by controlling the spatial frequency content of the targets (Burbeck, 1987a, 1988).

The next simplest explanation for the variation in threshold with separation is that separation discrimination thresholds are controlled by the accuracy of the local position information available for each target. This would mean that separation discrimination thresholds increase with separation because the retinal eccentricity of the targets increases with separation, thereby decreasing the local spatial resolution available for encoding local target position. Although a brief paper by Levi, Klein, and Yap (1988) supported that view, we have shown that retinal eccentricity is not an adequate explanation, and in fact, that it plays a rather small role in determining separation discrimination thresholds. We also found that, between 100 and 500 ms, exposure duration has a large effect on separation discrimination thresholds for an isolated target pair only at the very smallest—foveal—separations. Our work on this subject was reported in *Vision Research* in 1990; a copy of the paper is included as Appendix A. Collectively, this research showed that although the well-known properties of the multiscale contrast-dependent

stage affect the relative position thresholds (Burbeck, 1986), they are not sufficient by themselves to account for the data. Additional processing is required.

Taking a conservative view, we adopted a two-stage model in which the response space of the local spatial filters is acted on directly by a process that encodes the separations between excited regions in this space, independent of which spatial frequency range is providing the input. The insensitivity to the spatial characteristics of the objects being localized is a key feature of separation discrimination thresholds (Burbeck, 1987a; Toet et al., 1988). This two-stage working model formed the basis for the research conducted under this contract. Our approach was to ascribe as much of the variability in the separation discrimination thresholds as possible to the initial contrast-encoding stages. This is a parsimonious approach that maximizes the simplicity of the resulting model.

We modeled the contrast-encoding stage as a multiscale set of local spatial filters with the properties that filters tuned to higher spatial frequencies have smaller receptive fields, longer temporal contrast integration windows, and lower signal-to-noise ratios than those tuned to lower spatial frequencies. We also included the well-documented increase in minimum receptive field size with increasing retinal eccentricity.

This two-stage model proved to be an effective foundation for understanding the effect of the length of the individual target lines on separation discrimination thresholds. In our study of the effects of retinal eccentricity on separation discrimination thresholds (Appendix A), we conducted a small study on the effect of target size—knowing *a priori* that small targets would be more affected by eccentricity than would large targets. We found, surprisingly, that the story was more complicated. The effect of line length on separation discrimination thresholds varied with both separation and eccentricity, and those two variables interacted. Line length had its largest effect when the separation was small relative to the eccentricity. Dr. Yap, the postdoctoral fellow on this project, pursued this intriguing result and, in a major series of well-conceived and executed studies, was able to show that nearly all of the effect was attributable to spatial contrast integration—*i.e.*, to the first stage in the two-stage model. A manuscript reporting this research has been submitted to *Vision Research*; a copy is included as Appendix B.

Our first step in testing this two-stage model was to include extraneous background objects in the test stimulus, as shown in Figure 1 of Appendix C. If a separation discriminator were looking at the local spatial-filter response space, embedding the targets in an array of extraneous objects should interfere with performance. Following our usual practice of exploring the temporal dimension simultaneously with the spatial, we measured separation-discrimination

thresholds at exposure durations ranging from 100 to 500 ms. The results of this study were reported in *Vision Research* ; the paper is included as Appendix C. The inclusion of the time domain proved to be of central importance. If a long duration (500 ms) is used, embedding the targets in an array of like targets has little or no effect. However, as exposure duration is decreased, the strong differences in how the visual system performs the task with isolated and with embedded targets are clearly revealed. Thresholds are significantly more elevated at 100 ms when the targets are embedded than when they are not (see Figure 2 of Appendix C).

In our paper reporting this phenomenon, we were able to account for the data by postulating that the receptive fields providing the local position information are smaller (*i.e.*, tuned to higher spatial frequencies) when the targets are embedded in like objects than when they are not. This shift to higher spatial frequencies was thought to account for the higher thresholds obtained at short durations (because of the lower signal/noise ratio) and for the more pronounced dependence on exposure duration (because of the longer window of temporal contrast integration). Although this explanation was qualitatively satisfactory and adhered to our parsimonious approach, the effects seemed too large to be accounted for plausibly by temporal contrast integration. We had shown previously that separation discrimination thresholds decreased by about a factor of three between 1.5 and 5 times the contrast detection threshold and remained constant after that (Burbeck, 1987a). Subsequent study of the phenomenon continued to point away from our initial explanation. Details of our more recently completed research are given below.

A more plausible explanation is based on the fact that multiple distances are represented in the stimulus. According to this explanation, accurate separation discrimination takes longer when the targets are embedded because all of the spatial relationships between the lines are encoded on each trial, and it takes more time to encode more relationships. The choice of which spatial relationship to pay attention to is determined at a higher level of processing—in this case, processing based on the knowledge that the targets were the second and fifth lines in the array. We will refer to this explanation as the Sequential Acquisition of Spatial Structure (SASS) model. The SASS model has the advantage that it prevents us from having to incorporate a high-level abstraction (*i.e.*, which lines are the targets) into what we believe to be strictly visual encoding.

The idea that it takes longer for the visual system to calculate multiple distances than it does to calculate a single distance is supported by our study comparing separation discrimination and bisection thresholds. Again making use of the temporal dimension, we measured separation

discrimination and bisection thresholds for durations ranging from 17 to 500 ms. We found that bisection thresholds are higher than separation discrimination thresholds for short durations and lower than separation discrimination thresholds for long durations. The thresholds for the two tasks can be made to agree with one another at all durations if the bisection task is done by making two separation judgments serially: when the bisection data are plotted at one-half the nominal exposure duration (and the data are corrected for the lag between the two presentations in the separation discrimination task), then the data superimpose reasonably well. Performance reaches its peak value when about 120 ms is available for each separation judgment. The results of this study were reported in *Vision Research* in 1990; a copy of the paper is included as Appendix D.

As part of our study of the effects of embedding the targets in an array of other objects, we tested with stimuli in which the targets were white bars and the background objects were black bars. The targets popped out" of the background, and separation discrimination thresholds were quite low even at 100 ms. It seems that the visual system can ignore objects that are sufficiently different from the targets and encode the spatial relationship between the targets rapidly. In the context of the SASS model, this means that the sequence used in acquiring spatial structure is determined, in part, by the similarity of the objects. This is a desirable feature in a mechanism that contributes to perceptual organization.

We have been aware for some time of the possible connection between preattentive vision as described by, *e.g.*, Treisman and Gormican (1988) and the development of spatial structure. In a separation discrimination task, performance is impaired at short durations if both targets do not "pop out" of their backgrounds. To learn more about preattentive vision and the techniques commonly used to study it, the P.I. collaborated with Dr. Ben Kröse, who was at that time a postdoctoral fellow with Dr. Bela Julesz at the California Institute of Technology. We used the SRI eyetracker to stabilize the retinal image and presented a target at the same peripheral retinal location on every trial. We then examined the effect of distracters on reaction time for identifying the target. Targets and distracters were both either u's or n's. Even though no search was required to locate the target, reaction times were significantly elevated when the target was surrounded by a ring of distracters. This research was reported in *Spatial Vision* in 1990; a copy of the paper is included as Appendix E.

The finding that distracters retard identification even when the target location is known provides additional support for the idea that there is an automatic encoding of spatial structure that cannot be bypassed simply by intention. In these experiments, the target and background

were sufficiently similar that the spatial relationships were automatically encoded. Consistent with the SASS model, reaction times were more elevated when multiple distracters were present than when only one was used. However, adding a second ring of distracters had little effect, indicating that either the effect had a limited spatial extent or that some other simplification was imposed.

Our current research continues this theme of uncovering the temporal progression of the development of spatial links between parts of the visual stimulus. Definitions of what is meant by a part are just developing (*e.g.*, Kimia, Tannenbaum, and Zucker, 1989), but even without those definitions, using simple line and bar stimuli, we are uncovering the rules for establishing the links. All other things being equal, we have found that closer parts link together first. Some experiments we are currently conducting bear on this issue and show the direction that our research is heading.

Separation discrimination stimuli are presented in a temporal, two-interval, forced-choice procedure with a mask following presentation of each test to stop processing. The first test consists of three lines,

$$|_A \quad |_B\, |_C .$$

The second test consists of two lines,

$$|_{A'} \quad |_{B'} .$$

The observer's task is to determine which separation is larger, AB or A'B'. On each trial, one of these line pairs is separated by $s+n(\Delta s/2)$ and the other by $s-n(\Delta s/2)$, where s is the mean separation for the experiment, n varies from 1 to 5, and Δs is chosen so that the stimuli span the threshold range. The position of C varies randomly from trial to trial over a range that equals approximately $7\Delta s$. Its position is randomized to degrade its usefulness as a cue in the task. The mean position of C is a parameter of the experiments. The best strategy the observer could take would be to ignore C. However, he is not told when he is correct, or what his results are from an experimental session, so that he does not learn to compensate for any perceived bias. Thresholds and biases are measured using probit analysis techniques. Preliminary data on this phenomenon are shown in Figure 1 for two observers using a 0.75° separation.

When a short duration (100 ms) is used and BC < AB, observers bias their answers toward AB being farther apart than A'B'. If BC > AB ,then AB appears compressed. Our current view of this is that B and C are being linked perceptually; *i.e.*, that the tendency to see

AB as being farther apart when BC < AB arises from the tendency to assign a single location to the pair BC. When BC > AB, A and B are linked more strongly than B and C. Assignment of a single location to a pair of objects is, according to our theory, an indication that the two objects are being seen as parts of a single object. This assignment is not all or none: regions in space are linked to one another with varying degrees of strength. The weaker links form later (or more slowly).

AB appears longest when BC is approximately 1/2 of AB. The peak is presumably caused by a combination of the strength of the link between B and C diminishing as the distance BC increases, countered by the magnitude of the effect increasing as BC increases. It is interesting that B is pulled perceptually toward C even when BC is a fairly large fraction of AB. When a long duration (500 ms) was used, one observer ignored C but the other did not. An even longer duration will be tried with the observer who could not ignore C.

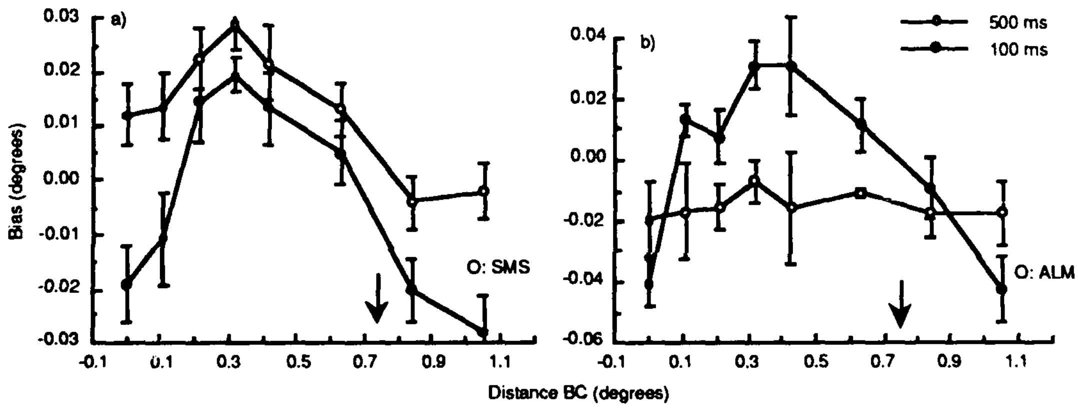

Figure 1 Shift in perceived separation caused by the presence of a third line. Mean separation to be judged was 0.75°. The abscissa is the mean distance between one of the target lines and the third (extraneous) line. Data are shown for two durations and two observers.

Although it is extremely simple, or perhaps because it is, we believe that this paradigm holds considerable promise for revealing the rules of the initial spatial linkage performed by the human visual system. This would be an important step in connecting the initial stages of visual processing with perceptual organization. We hypothesize that the links that are formed first when viewing a new stimulus are those that control perceptual grouping. Links that form later or more slowly provide information about the global spatial structure of the scene. The results we obtained using targets embedded in an array of like targets indicate that it is not necessary for objects to group perceptually for low separation-discrimination thresholds to be achieved. The links that form later are sufficient to support accurate spatial judgments. However, our results

also suggest that perceptual grouping may be necessary to achieve low separation-discrimination thresholds when a brief duration is used. Our work in progress supports that view. We intend to vary the spatial characteristics of the individual objects to determine the power of similarity along various dimensions in controlling the strength of the link.

We also are exploring the importance of temporal synchronicity in the rapid creation of spatial links. Preliminary data have been obtained using the paradigm in which the target pair is embedded in an array of like objects. If the background array is presented for 200 ms before the targets are presented and the targets and background are then left on together for 100 ms, separation-discrimination thresholds are as low as if the background were not there. The temporal synchronicity of the targets and asynchronicity of the background bars relative to the targets is sufficient to support a rapid link between the two targets. This research is being continued with this paradigm and with the three-line paradigm described above to determine the temporal tuning of this linking rule.

A complete study of the linking rules would require manipulation of many stimulus variables. Our initial focus will be on these:

- Internal spatial characteristics—using standard Gabor patch stimuli to provide a means of varying the internal scale systematically
- Spatial scale or size of the individual objects
- Relative orientations of the individual objects
- Temporal synchronicity of the objects
- Contrast polarity. (We already have evidence that black and white bars link more slowly than do white and white bars, when both are present.)

One hypothesis we will be testing is that this stage of perceptual linking is based on synchronous oscillations in human visual cortex that are analogous to those found in cat cortex between neurons tuned to similar orientations (Gray and Singer, 1989). This hypothesis predicts that linking between unconnected stimuli whose orientations are orthogonal should be poor. Casual inspection of a horizontal/vertical pair of stimuli suggests that linking will be slow. However, our ability to conduct this experiment rigorously has been impaired by our inability to generate an effective masking stimulus with our essentially one-dimensional display apparatus. The new display system ordered will enable UNC to continue this research.

Our research on the development of spatial structure has direct application to understanding how the visual system constructs the geometry of a visual scene, turning a two-dimensional plane into a set of 2-manifolds in three-dimensional space that are the perceptual objects. The linking that we observe in our experiments may be the visual system's first step in identifying regions as belonging to a common manifold. Our mastery of the contributions to this phenomenon of the initial stages of processing allows us to isolate this higher level of processing and avoid the confusions and complications that arise when the effective signal strength arising from the various stimuli is not carefully controlled. Lack of control of signal strength is a problem with many reaction-time studies of perceptual grouping.

The fact that spatial structure develops over hundreds of ms at the level we are studying also has profound implications for the rapid analysis of displayed images. A subtle spatial relationship may be missed during a scan of an image, even though the relationship is clearly suprathreshold because the initial links pull one part of the image away from another perceptually. We are pursuing this application in the context of presentation and analysis of medical images under separate sponsorship. (See below.)

As we uncover the rules for spatial linking, we will also work on developing a mathematical characterization that captures the temporal development of spatial structure at this stage of processing. Having control over the responses of the initial spatial filters simplifies this task considerably. We can begin our modeling with conditions in which the responses from the initial stage do not vary with exposure duration or with the spatial characteristics of the targets.

B. COMPARISON OF ORIENTATION AND SEPARATION DISCRIMINATION USING TWO EXPERIMENTAL PARADIGMS

A study, done in collaboration with Dr. Lex Toet of Institute for Perception TNO (in Soesterberg, The Netherlands), on the relationship between orientation discrimination and separation discrimination, is now complete. Dr. Toet, who visited our laboratories for one month in 1989 under sponsorship of SRI International, is preparing a manuscript on our joint work. The research was also reported at ARVO (Toet, Yap, and Burbeck, 1990). In that research, separation discrimination and orientation discrimination thresholds were compared using a two-interval paradigm that eliminates differences that might arise because of differences in the variability of the remembered referent in the two tasks. Data were obtained at a wide range of eccentricities, separations, and orientations. Orientation discrimination thresholds were always equal to or lower than the separation discrimination thresholds, depending on the observer. The data suggest

that different mechanisms are involved in these two tasks. Data were also obtained using a one-interval paradigm, following up research begun by Dan Swift of the University of Michigan—and the PI—and reported in Burbeck and Swift (1988). Contrary to our initial expectations, the differences between the orientation-discrimination thresholds obtained with one-interval and two-interval paradigms were not smaller at the primary orientations. However, there were large intersubject differences in the effect of changing from two intervals to one. The data argue for the use of two-interval paradigms whenever possible.

C. CONTEXT EFFECTS IN SEPARATION DISCRIMINATION: SPATIAL-FREQUENCY INDEPENDENCE

As noted, the spatial frequency shift model of the effect of embedding the targets in an array of like objects was not completely satisfactory. The effects were sometimes too large to be accounted for plausibly by temporal contrast integration. The idea that the visual system changes actively from one spatial scale of representation to another when the field becomes crowded was a potentially important conclusion, so we decided to pursue the issue in more depth, critically testing our hypothesis.

In this study, we tested the spatial frequency shift model by controlling the spatial frequency range and the effective contrast of the stimuli. Separation-discrimination thresholds were measured using narrow-band stimuli for both the targets and the background objects. Stimulus contrast was set to a constant multiple of the observer's contrast detection threshold. If the effect of embedding the targets in an array of like objects is to shift the relevant spatial frequency range, then we should see better performance when the stimuli are of high spatial frequency than when their spatial frequency is low. We know from previous studies that when a pair of targets is presented on a uniform field, their spatial frequency has no effect on the separation-discrimination threshold, provided signal strength is adequate. Therefore, if separation-discrimination thresholds for embedded targets are elevated at low spatial frequencies, the frequency shift model would be supported. If there is no effect of spatial frequency the model would have to be rejected.

We also examined the effect of target blur on separation discrimination thresholds at two separations as a step in understanding the effect of the diffusion screen on separation-discrimination thresholds with embedded targets and brief durations (Appendix C). This study also addressed the more general question of the effect of blur on separation discrimination thresholds (Toet *et al.*, 1987).

1. Equating Effective Contrast across Spatial Frequency and Exposure Duration

Effective contrast was equated across spatial frequency and exposure duration by setting target contrast equal to a fixed multiple of the contrast-detection threshold for the target in each condition. This approach assumes that the detection threshold is a measure of the contrast gain of the responsible units and that the units responsible for detection threshold are the same as those responsible for encoding high-contrast stimuli. This approach has been used previously with good effect, in the sense that it simplified the resulting data. The test of the validity of our assumptions in this study will be whether they simplify the resulting data.

Toet and Koenderink (1988) used threshold-contrast stimuli to avoid these assumptions about the relationship between detection threshold and the encoding of high-contrast stimuli. This approach is simpler from a theoretical perspective but it has the disadvantage that data collection is unusually onerous and the resulting data are noisier than those obtained with high-contrast stimuli.

Contrast-detection thresholds for the targets (at the retinal locations that the targets occupy in the separation-discrimination task) were measured for each spatial frequency at both exposure durations used. The results, which follow typical contrast-sensitivity patterns, are shown in Figure 2. To minimize any residual contrast effects that would result from eye movements or other noise in the contrast-threshold measurements, target contrast was set at the highest possible integral multiple for each observer (the limit being determined by the highest contrast threshold). For both observers, this factor was 5. Because contrast has no effect on separation discrimination thresholds beyond 3 to 5 times the detection threshold (Burbeck, 1987a) maximizing stimulus contrast will minimize contrast effects.

2. Effects of Spatial Frequency and Exposure Duration on Separation Discrimination Thresholds with Embedded Targets

Separation discrimination thresholds for large separations between bar targets can be elevated at short durations by embedding the targets in an array of parallel bars. This effect has been attributed to spatiotemporal interaction in the contrast-encoding stage by postulating that smaller spatial filters detect the individual target bars when the targets are embedded in an array than when the targets are isolated. (The smaller filters integrate contrast over a longer duration; hence the effect.) To test this explanation, we (1) used targets that primarily stimulate a small

range of spatial frequency, (2) varied that range, and (3) held the effective contrast of the targets and background objects constant across spatial frequency and duration.

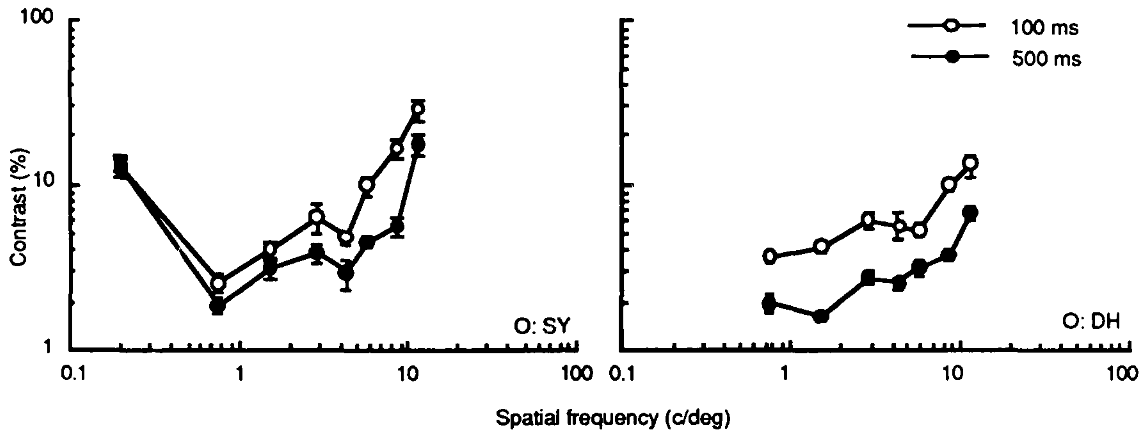

Figure 2 Contrast sensitivity for two observers for target lines presented approximately 1.5 degrees in the periphery. Data are shown for two exposure durations.

If the change in the effect of exposure duration that occurs when targets are embedded is entirely attributable to a shift in the relevant spatial-frequency range, then restricting the spatial-frequency range should prevent this shift. This means that thresholds should be higher at low spatial frequencies where, the frequency-shift theory asserts, the background bars interfere with encoding the individual target bar locations, than at higher spatial frequencies where targets can be detected individually. Furthermore, the effect of exposure duration should be eliminated.

The results for three observers are shown in Figure 3. Spatial frequency has no consistent effect on the separation-discrimination thresholds, implying that all spatial frequencies in the range tested support this discrimination equally well. No shift in the spatial-frequency range being used is required to achieve optimal performance. Furthermore, the large effect of exposure duration remains even though the effective contrasts of the 100- and 500-ms stimuli have been equated. Thus, the effect is not attributable to temporal contrast integration.

3. Diffusion Screen Results

Given that the effect of embedding the targets in an array of like objects is independent of the spatial-frequency range of the stimulus, we are left with the problem of why the diffusion screen has more effect at 100 ms with the embedded targets than it does in any of the other three conditions (isolated targets at 100 or 500 ms and embedded targets at 500 ms). Two obvious possibilities are that the effect results from a reduction in effective contrast across all usable spatial frequencies or that it results from an increase in the blur of the targets and background

objects. The first possibility is unsatisfactory quantitatively: the threshold elevations are too large to be accounted for plausibly in terms of temporal contrast integration. The second explanation requires that target blur have a larger effect at 100 ms than at 500 ms when the targets are embedded and little effect at either duration when the targets are isolated.

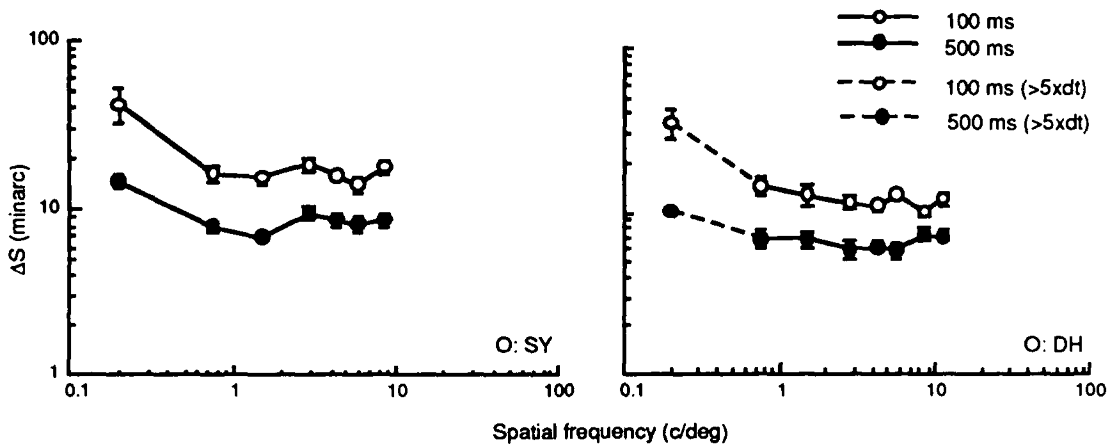

Figure 3 Separation discrimination thresholds for targets embedded in an array of four parallel flanking bars as a function of the spatial frequency of the targets and flanking bars (always equal). Data are shown for two durations for each of two observers.

The largest target blur that could be used in the embedded condition with a 3° target separation was the leftmost datum in Figure 3. Although increasing target blur to this size had a small effect, it did not preferentially increase thresholds for the brief durations, as occurred when the diffusion screen was used. Larger blurs could not be used because of the large trial-to-trial variation in the distance between the targets and their nearest background bars. To determine whether a larger degree of blur has more effect at short durations when the separation between adjacent pairs of lines is small, as it is in the embedded condition, we measured the effect of target blur using isolated targets at two separations, one approximating the separation between the target and its nearest background bar (1°) and one approximating the target separation (3°). Two exposure durations were used, 100 and 500 ms.

Separation discrimination thresholds for two separations, two exposure durations, and two observers are shown in Figure 4. Target blur has no significant effect on separation discrimination thresholds over the range tested. The effect of target blur does not scale with separation and is independent of exposure duration.

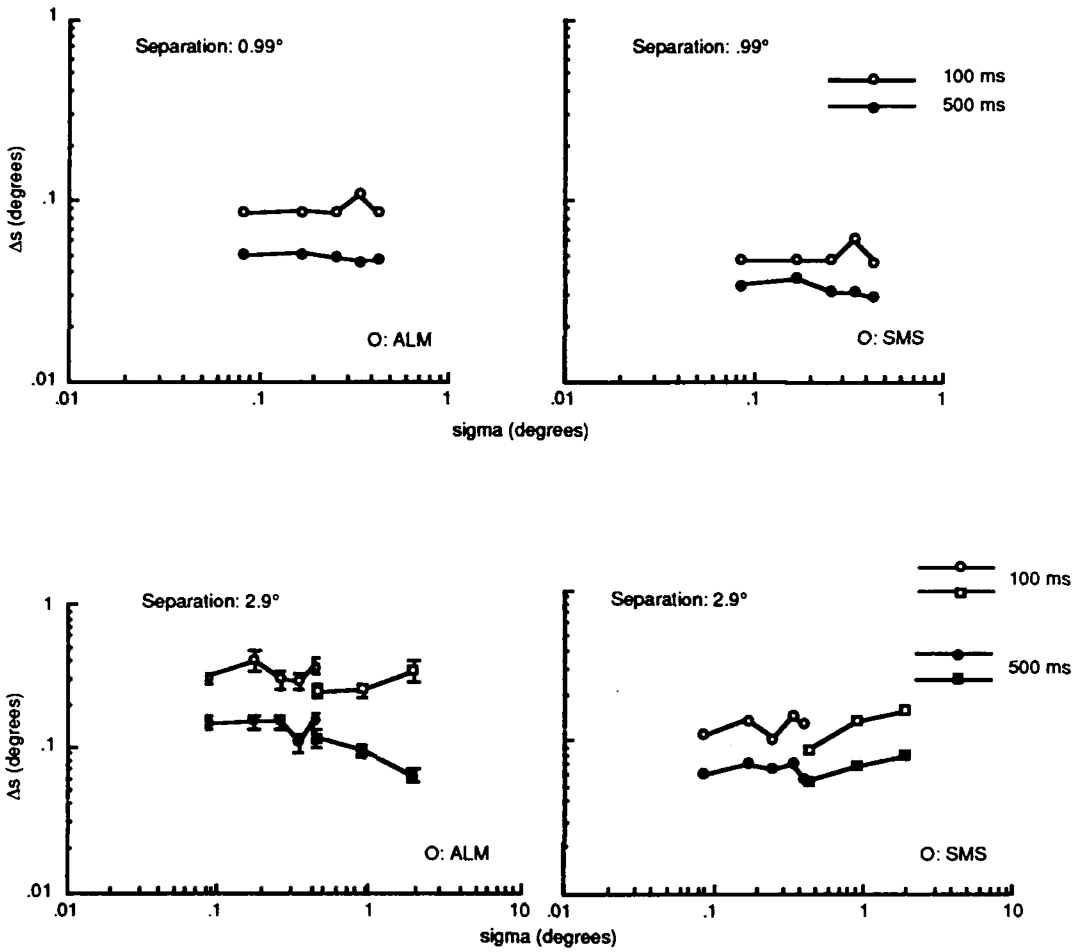

Figure 4 Separation discrimination thresholds for a pair of target bars measured as a function of the blur of the individual bars. Data are shown for two observers and two durations at two separations. The change from circular to square symbols indicates a change in viewing distance.

There is nothing in these data to support the idea that target blur is of general importance in separation discrimination thresholds. This information is of general interest because of the finding by Toet *et al.* (1987) that increasing the blur increases separation-discrimination thresholds. In that study, the separation between the targets increased with the degree of blur, so the two factors are intertwined. In the present experiment, the two factors have been manipulated independently and blur has been found to have no effect. If blur is an important factor when the targets are embedded, then its importance is specific to that condition.

4. Interobserver Differences

The interobserver variation is larger than indicated by the data shown here. For some observers, we could not measure thresholds for the 100-ms duration with the embedded targets using the 0.04° to 0.3° range of Δs that was available. (The separation between the inner flanking lines limited the range of Δs that could be used. When the range of Δs was increased, the minimum separation between the two inner parallel bars decreased and it could not go below zero.) Table 1 summarizes the data for eight naive observers obtained during the first three sessions with each paradigm. The data with the two-line stimulus were obtained before the six-line experiments were begun, to give the observers practice with the easier task.

Table 1. VARIATION IN SEPARATION DISCRIMINATION THRESHOLDS

Observer	2 Line	6 Line
VLS	.4466 ± .0415	*
REJ	.1935 ± .0195	.4069 ± .0319
SMS	.1512 ± .0145	.6930± .0903
MAG	.2544 ± .0242	*
RMC	.2501 ± .0180	*
ALM	.2459 ± .0276	*
STH	.1853 ± .0232	.2353 ± .0175
HRV	.3282 ± .0528	1.6559 ± .4766

* Thresholds were too high to be measured with the range of Δs that was available.

5. Conclusions

Our current view is that when the target and background objects are similar, the visual system sequentially encodes all of the spatial relations between them, which takes time. This theory is still in its preliminary stages and will require elaboration. The experiments we are conducting, particularly those using the three-line paradigm described above, should reveal the underlying mechanisms of spatial linking more clearly, providing a broader foundation for development and testing of this theory.

D. PERCEIVED SPATIAL FREQUENCY AND SPATIAL FREQUENCY DISCRIMINATION THRESHOLDS

This study has a long history, beginning with a study by Regan and Beverly [1983] showing that spatial frequency discrimination thresholds were elevated following adaptation to a high contrast grating. Unlike contrast detection thresholds, which are elevated most at the adapting frequency, spatial frequency discrimination thresholds were found to be elevated most at about 2 1/2 times the adapting frequency. We had recently shown (Burbeck, 1987b) that frequency discrimination is done on the basis of the perceived spatial frequency, not on the basis of the retinal spatial frequency. Therefore, we were intrigued to discover that the adapting field diameter that Regan and Beverly used was exactly 2 1/2 times that of the test field. This meant that the largest adapting effect occurred when the test and adapting gratings had the same number of cycles. In the darkened room with monocular viewing, these two stimuli may have had the same perceived spatial frequency.

Pursuing this intriguing possibility, we attempted to replicate Regan and Beverly's results. Much to our disappointment, we were unable to get the effect. We wrote up that fact, but the paper was not accepted. The editor, quite reasonably, thought that a refutation should contain at least as much data as the original report.

Satisfying this requirement would have meant collecting data for hundreds of hours, only to show that there were no large effects. This was not an appealing prospect. We decided instead to investigate an interesting theoretical relationship that we had uncovered in the course of thinking about the issues. We noted that the perceived spatial frequency shift (PSFS) predicted that frequency discrimination thresholds should change following pattern adaptation. At the adapting frequency, thresholds should be lowered because frequencies sightly higher than the adapting frequency look higher still and those lower look lower still, enhancing the perceptual difference. At frequencies more removed from the adapting frequency, discrimination thresholds should be elevated because the perceived frequencies are compressed in the S-shaped curve characteristic of the PSFS.

We investigated this relationship experimentally, collecting both PSFS data and frequency discrimination thresholds at the same time (as the bias and threshold obtained in a frequency discrimination experiment with no right/wrong feedback). Our frequency discrimination results for two observers are shown in Figure 5 with some of Regan and Beverly's data for comparison. We found that thresholds were elevated significantly more when the test frequency was higher

than the adapting frequency than when the test frequency was lower. However, the effect was very small. This replicated our previous failure to find the large effects reported by Regan and Beverly (see also Thomas and Greenlee, 1990).

We obtained the usual PSFS in these experiments, with a magnitude comparable to that found by Klein *et al.* (1974), which was much smaller than the original effect reported by Blakemore *et al.* (1972). From our data we calculated the frequency discrimination threshold elevation predicted by the change in appearance of the gratings. This prediction is plotted with the actual data obtained in Figure 6. Clearly the effect of pattern adaptation on frequency discrimination cannot be accounted for by the change in the appearance of the gratings. Another factor must be involved in determining these thresholds.

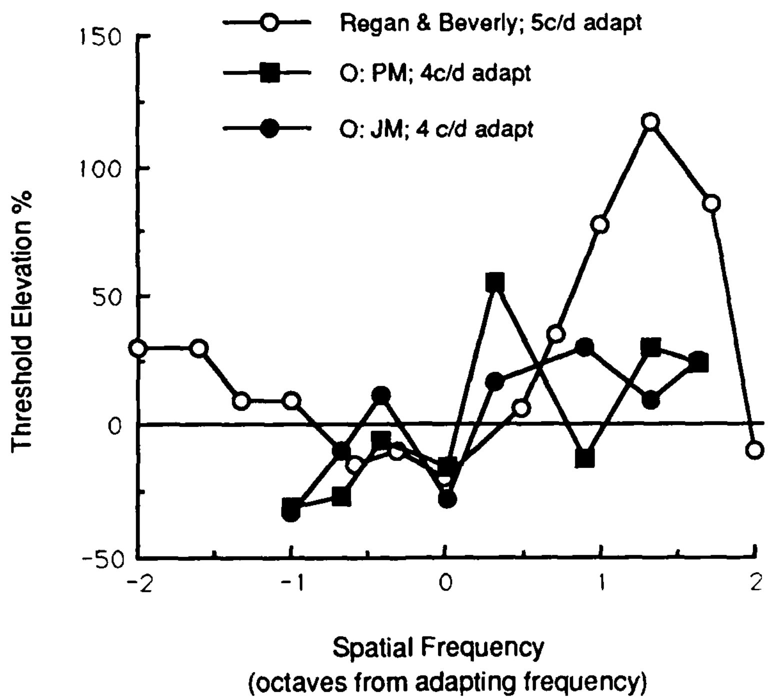

Figure 5 Change in spatial-frequency discrimination thresholds following adaptation to a high-contrast grating. The filled circles are data obtained for two observers in our laboratory. The open circles are from Figure 1 of Regan and Beverly (1983).

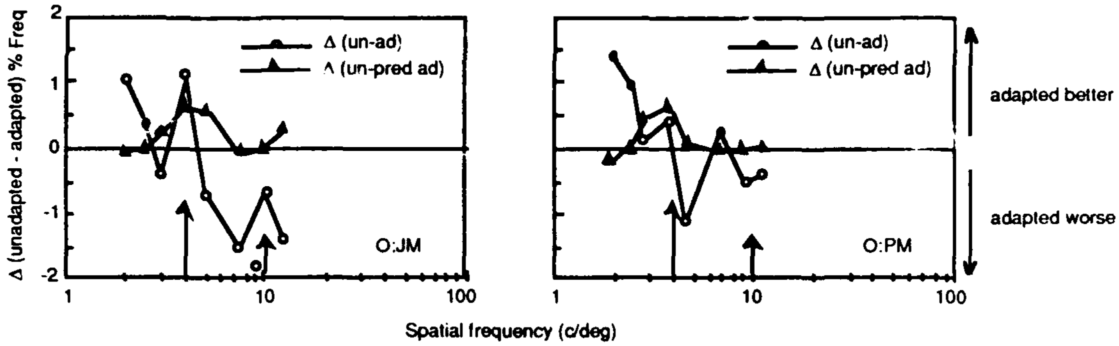

Figure 6 The change in spatial-frequency discrimination thresholds following adaptation to a high-contrast grating predicted by the perceived spatial-frequency shift (obtained in simultaneous measurements for each observer), shown by the filled symbols. Also shown for comparison are the data actually obtained, shown by the open symbols. Data are shown for two observers.

These results on frequency discrimination raise more questions that they answer. The effect of pattern adaptation on frequency discrimination can be small, as we found, and is certainly not robust. Furthermore, it is unclear whether frequency discrimination is done on the basis of the global frequency or on the basis of the bar-to-bar separation (Hirsch and Hylton, 1982). Because of these complexities, we are not pursuing the issues further, although we are preparing a manuscript on what we have learned. We conclude that there is not yet a firm foundation for the theory that spatial frequency discrimination is based on the responses of spatial filters tuned to frequencies lower than the test frequencies. The underlying processes seem to be decidedly more complex than that.

Questions about spatial relationships seem more directly and appropriately addressed in the space domain, particularly in light of the findings that the spatial frequency content of the scene does not have a direct effect on the measured threshold (Burbeck 1987a, 1988, and see above) This has been and will continue to be our primary approach. We manipulate the spatial frequency content of the individual targets only to determine the connections between the initial stages of processing and the higher level stages at which spatial structure is inferred.

III PUBLICATIONS, PRESENTATIONS, AND OTHER PROFESSIONAL PARTICIPATION

A. WRITTEN PUBLICATIONS

Kröse, Ben J.A., and Christina A. Burbeck, 1989: Spatial Interactions in Rapid Pattern Discrimination. *Spatial Vision* **4,** 211-222.

Burbeck, Christina A., and Yen Lee Yap, 1990: Spatial-Filter Selection in Large-Scale Spatial-Interval Discrimination. *Vision Research* **300**, 263-272.

Burbeck, Christina A., and Yen Lee Yap, 1990: Two Mechanisms for Localization? Evidence for Separation-Dependent and Separation-Independent Processing of Position Information. *Vision Research* **30**, 739-750.

Burbeck, Christina A., and Yen Lee Yap, 1990: Spatiotemporal Limitations in Bisection and Separation Discrimination. *Vision Research* **30**, 1573-1586.

Burbeck, Christina A., Encoding Spatial Relations. In R.J. Watt (Ed.), *Pattern Recognition,* Vol. XII of Vision and Visual Dysfunction. London: Macmillan (in press).

Yap, Yen Lee. The Length Effect in Separation Discrimination. Submitted to *Vision Research.*

Toet, Lex, Yen Lee Yap, and Christina A. Burbeck. Comparison of Orientation and Separation Discrimination. (In preparation).

Burbeck, Christina A., and Yen Lee Yap. Context Effects in Separation Discrimination: Spatial-Frequency Independence. (In preparation).

Burbeck, Christina A., and Yen Lee Yap. Perceived Spatial Frequency and Spatial Frequency Discrimination Thresholds. (In preparation).

B. ORAL PRESENTATIONS

Burbeck, Christina A., and Dan J. Swift, 1988. "The Remembered Referent in Separation Discrimination and Vernier Acuity Tasks," Annual Meeting, Optical Society of America, Santa Clara, CA, (October 31 - November 4).

Kelly, D.H., and Christina A. Burbeck, 1988. "Enhancement of Contrast Sensitivity by Microsaccades," Annual Meeting, Optical Society of America, Santa Clara, CA (October 31 - November 4).

Yap, Yen Lee, and Christina A. Burbeck, 1988. "Two Mechanisms for Large-Scale Localization," Annual Meeting, Optical Society of America, Santa Clara, CA (October 31 - November 4).

Yap, Yen Lee, and Christina A. Burbeck,1989. "Integrating Size Information: Temporal Integration in Bisection and Separation Discrimination," poster presented at ARVO Annual Meeting, Sarasota, FL (April 30 - May 5).

Burbeck, Christina A., and Yen Lee Yap, 1989. "Integrating Size Information: Using the Second Spatial Dimension," ARVO Annual Meeting, Sarasota, FL (April 30 - May 5).

Yap, Yen Lee, and Christina A. Burbeck, 1990. "Spatial filter selection in separation discrimination," ARVO Annual Meeting, Sarasota, FL (April 29 - May 4).

Toet, A., Yen Lee Yap, and Christina A. Burbeck, 1990. "Single process for 2-dot separation discrimination and 2-dot orientation discrimination?" ARVO Annual Meeting, Sarasota, FL (April 29 - May 4).

C. CONSULTATIVE AND ADVISORY FUNCTIONS

Dr. Burbeck is serving on the NSF Review Panel for the Sensory Systems section, from Fall 1989 through Spring 1992.

Dr. Burbeck served as an ad hoc reviewer for the NIH National Eye Institute, Study Section B in June of 1988.

Under this contract, we carried out research on the effects of foveal scotomas on performance of a wide range of visual tasks. This research was sponsored by DARPA, and was described in Appendix F of the Annual Report for 1989.

Dr. Burbeck is working with the Medical Image Presentation Program in UNC's Computer Science Department, advising on the conduct of vision research experiments that are germane to the problem of how best to display medical images. The research findings and theories developed under this contract are being incorporated into that program. [Dr. Burbeck has been receiving a small level of support (12% of her time) from that project since August, 1990.]

Dr. Burbeck is serving on the doctoral committees of three students in the Computer Science Department. She also is supervising an independent study in vision by an undergraduate student majoring in psychology.

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Toet, A., and J.J. Koenderink, 1988: Differential spatial displacement discrimination thresholds for Gabor patches. *Vision Res.*, **28**, 133-143

Toet, A., H.L. van Ekhout, J.J. Simons, and J.J. Koenderink, 1987: Scale invariant features of differential spatial displacement. *Vision Res.*, **28**, 133-143

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Appendix A

TWO MECHANISMS FOR LOCALIZATION? EVIDENCE FOR SEPARATION-DEPENDENT AND SEPARATION-INDEPENDENT PROCESSING OF POSITION INFORMATION

TWO MECHANISMS FOR LOCALIZATION? EVIDENCE FOR SEPARATION-DEPENDENT AND SEPARATION-INDEPENDENT PROCESSING OF POSITION INFORMATION

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Abstract—The Weber function for separation—i.e. Δs as a function of separation s—is typically measured using a pair of targets presented roughly symmetrically relative to the fovea. With this paradigm, as the separation increases, the eccentricity of the individual targets increases also. To disentangle the effects of separation and eccentricity on the Weber function for separation, we systematically examined each of these variables and also examined the effects of target size and exposure duration. Separation discrimination thresholds were measured for average separations from 3 to 6 deg across a wide range of eccentricities, and for eccentricities of 2.5–10 deg for a range of separations. The dependence of threshold on target size was measured by varying the length of the stimuli from 1 to 120 min arc; the dependence on exposure duration was measured using durations of 100 and 500 msec at 10 deg eccentricity for comparison with data collected previously at smaller eccentricities. We found that for separations less than the eccentricity of the targets, thresholds depend primarily on separation; for larger separations, thresholds depend solely on eccentricity. In general, unless the targets are very small or quite brief, the spatial and temporal characteristics of the targets are not major contributors to the slope of the Weber function. Two mechanisms are proposed to account for thresholds in the two regions, one separation-dependent and one separation-independent.

Separation discrimination Size Eccentricity Periphery Spatial summation Temporal summation Spatial vision

ECCENTRICITY EFFECTS FOR FIXED SEPARATIONS

Introduction

When measured in the standard way, with fovea-centered stimuli, separation discrimination and bisection thresholds increase almost proportionally with separation; that is, the Weber function for separation—Δs measured as a function of s—is linear on a log scale with a slope of approximately one (Fechner, 1860; Volkmann, 1858; Westheimer & McKee, 1977; Andrews & Miller, 1978; Levi & Klein, 1983; Klein & Levi, 1985, 1987; Burbeck, 1987; Toet, van Ekhout, Simons & Koenderink, 1987). Although this is one of the fundamental properties of localization thresholds, it remains unexplained. Several local-spatial-filter models of spatial vision have been proposed to account for data obtained at small separations (e.g. Wilson & Gelb, 1984; Klein & Levi, 1985). However, localization thresholds cannot, in general, be accounted for solely by the responses of individual local spatial filters (Morgan & Ward, 1985; Burbeck, 1987, 1988; Toet et al., 1987; Toet & Koenderink, 1988). In particular, the Weber function for separation cannot be explained by an increase in spatial uncertainty with decreasing spatial frequency. An alternative explanation must be found. Levi, Klein and Yap (1988) suggest that localization thresholds increase with increasing separation because the retinal eccentricity of the individual targets increases with increasing separation when measured with fovea-centered stimuli. Supporting this theory are experiments they conducted in which bisection thresholds were measured for targets positioned on a chord of an isoeccentric arc, 10 deg from the fovea. They found little variation in threshold with separation, for separations ranging from 3.5 to 10 deg, and concluded that the slope of the Weber function for separation was simply a consequence of retinal inhomogeneity. According to this theory, the decrease in spatial sampling density with increasing eccentricity is the sole determinant of the slope of the Weber function for separation.

If the Weber function for separation is actually independent of separation, then holding the separation constant and varying only the eccentricity should yield the traditional Weber function for separation, with a slope of almost unity. In our first experiment we tested this possibility by measuring separation discrimination thresholds as a function of target eccentricity for a fixed separation. Since contrast sensitivity studies show that the effect of eccentricity depends on the spatial characteristics of the stimulus (e.g. Koenderink, Bouman, Bueno de Mesquita & Slappendel, 1978; Rovamo, Virsu & Nasanen, 1978), we chose large, high-contrast bar targets to try to bypass limitations imposed at distal stages of visual processing.

Methods

The stimuli were all generated on a CRT with a mean luminance of $90\,cd/m^2$ (Conrac Model 2400, 48.3-cm diagonal, 60-Hz non-interlaced frame rate, 512×512 pixels). For the first experiment, each stimulus was a pair of horizontal bars, presented at 90% contrast $[(L_{max} - L_{background})/L_{background}]$ with abrupt onset and termination for a duration of 500 msec. The individual bars were nearly square, measuring 1.3 deg horizontally $\times$ 1.1 deg vertically. The bar pairs were presented with an average vertical separation of 4.2 deg at a viewing distance of 1 m. Viewing was monocular with the right eye.

The vertical separation between the targets was varied from trial to trial to determine the separation discrimination threshold. The observer's task was to report whether the separation presented on a given trial was larger or smaller than the average separation that he had seen on previous trials. Right/wrong auditory feedback for this single-criterion task was given after each trial. Practice trials at the beginning of each data collection session enabled the observer to learn the average separation.

The method of constant stimuli was used with 14 separations, $s \pm n\Delta s$ where n is an integer ranging from 1 to 7. The choice of Δs was determined from pilot runs. A run consisted of 154 trials, of which the first 14 were practice and were excluded from threshold calculations. The rest of the run consisted of 10 blocks of the fourteen test separations with a randomized order of presentation within each block. As many as 15 runs were conducted for a given observer and eccentricity to ensure that practice effects did not affect the final results. No practice effects were found for either of our experienced observers in this task. We calculated thresholds at the 84% correct level using a program that optimized the likelihood of the best-fitting cumulative normal function, which is equivalent to standard probit analysis. This program also generated the standard errors, which are shown.

To prevent the observer from using the edges of the display as cues to position, the stimulus was centered horizontally on the display so that it was well away from the edges. We also varied the vertical position of the stimulus on the display randomly from trial to trial within a range of ± 0.7 deg.

For the nonfovea-centered stimuli, the stimuli were presented to the nasal retina. Eccentricity was varied by instructing the observer to fixate a small fixation dot optically superimposed on the display and visible at all times. For the fovea-centered stimuli, no fixation marks were used, and the observer was instructed to fixate the center of the display.

Results

Data, plotted as a function of the eccentricity of the targets, are shown in Fig. 1 for two observers. Between 2 and 10–15 deg, eccentricity had little or no effect. However, because the stimulus was displaced vertically by a random amount from trial to trial (up to 0.7 deg variation in the vertical placement), there could be a small dependence on eccentricity at the smallest eccentricities that was not evident in the data. On the other hand, if eccentricity were solely responsible for the slope of the Weber function, then the threshold would have nearly doubled whenever the eccentricity doubled. This clearly did not occur for these stimuli for eccentricities less than 10 or 15 deg. Beyond 15 deg, larger eccentricity effects were obtained.

To determine whether the insensitivity to eccentricity at small eccentricities was specific to our choice of stimuli, we repeated the experiment with smaller stimuli and a briefer presentation, using two new separations, 2.9 and 5.9 deg. The targets were 4×30 min arc, presented for 200 msec. Data for the two observers are shown in Fig. 2. For eccentricities up to 10–15 deg, the effect of eccentricity was similar to that seen with the larger targets, indicating that the small effect of eccentricity in this region is not specific to the stimulus used. For separations between 2 and 10 deg, the effect of eccentricity was never large enough to account for the slope of the fovea-centered Weber function.

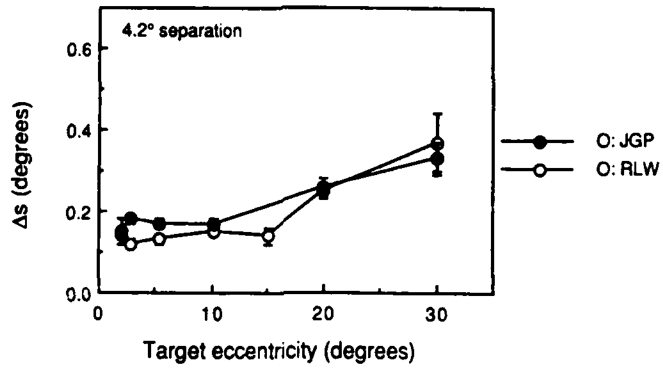

Fig. 1. Separation discrimination thresholds plotted as a function of eccentricity for a separation of 4.2 deg for observers JGP and RLW. Targets used were bars 1.3 deg long and 1.1 deg tall lasting 500 msec. Thresholds show little dependence on eccentricity up to 10 or 15 deg. For larger eccentricities, the eccentricity effect was pronounced.

Palmer and Murakami (1987) also reported similarly small eccentricity effects.

At larger eccentricities, thresholds obtained with these smaller, briefer targets increased more steeply with eccentricity than did thresholds for the larger, longer-duration targets. The amount of that increase depended on the separation, the rise for the 2.9 deg separation being greater than for the 5.9 deg separation. This rise could not be caused by the limits of spatial resolution because even at 30 deg eccentricity, the resolution threshold is less than 1 deg (Wertheim, 1891; Mandelbaum & Sloan, 1947; Weymouth, 1958; Frisen & Glansholm, 1975; Rovamo & Virsu, 1979). The rise could also not be caused by spatial interference,

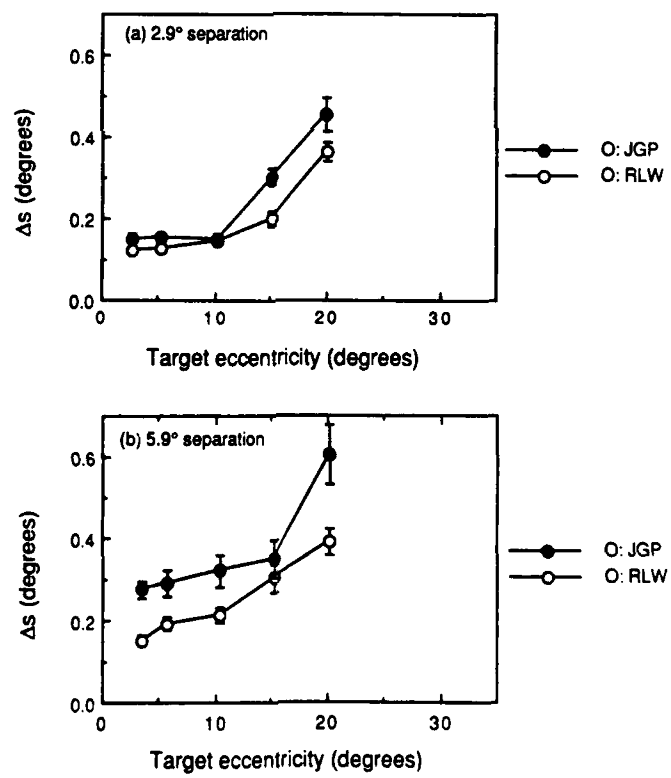

Fig. 2. Separation discrimination thresholds plotted as a function of eccentricity for a separation of 2.9 (a) and 5.9 deg (b) for observers JGP and RLW. Targets used were rectangles 30 min arc long and 4 min arc tall lasting 200 msec. For the separation of 2.9 deg, thresholds were constant up to 10 deg eccentricity and increased for larger eccentricities. For the separation of 5.9 deg, thresholds showed a slight dependence on eccentricity at all eccentricities for observer RLW but a steeper slope for eccentricities greater than 15 deg for observer JGP.

because spatial interference occurs in separation discrimination tasks only when at least one target is flanked on both sides by other targets (Westheimer, Shimamura & McKee, 1976; Badcock & Westheimer, 1985a,b; Yap, Levi & Klein, 1989). In subsequent experiments we investigate how the eccentricity effect evident in these data depends on the spatial and temporal characteristics of the targets, and on their separation.

SEPARATION EFFECTS FOR FIXED ECCENTRICITES

Introduction

The data of Figs 1 and 2 show thresholds for separations of 3–6 deg increasing only slightly as the eccentricity was changed from 2 to 10 deg. This suggests that, in that range, separation is the primary determinant of the slope of the Weber function for separation discrimination. To extend our understanding of how separation and eccentricity contribute to separation discrimination thresholds over a larger range of values, we measured separation discrimination thresholds for stimuli presented on isoeccentric arcs at 2.5, 5 and 10 deg eccentricity on the nasal retina of the right eye. Prior to that, we replicated the traditional Weber function for separation using fovea-centered stimuli.

Methods

The targets were rectangles, 4 min arc high by 32 min arc long, presented for 150 msec (for consistency with Levi et al., 1988). For the fovea-centered conditions we used a viewing distance of 106 cm for separations up to 5 deg and a viewing distance of 53 cm for all other separations. For the isoeccentric conditions, we used several viewing distances: 212, 106 and 53 cm. For 2.5 deg eccentricity, we used 212 cm for the two smallest separations and 106 cm for the other separations. For 5 deg eccentricity, we used 106 cm for the 1.4 deg separation and 53 cm for the other separations. For 10 deg eccentricity, we used 53 cm for all separations. To prevent the observer from using the distance from each target to the edge of the screen as a cue to the separation between the targets, the overall vertical position of the stimulus was changed from trial to trial by an amount that varied with eccentricity. At 2.5 deg eccentricity, the maximum vertical displacement was ± 0.17 deg for the two smallest separations and ± 0.35 deg for the other separations. At 5 deg eccentricity, the stimulus was displaced up to ± 0.35 deg for the separation of 1.4 deg and ± 0.7 deg for the other separations. At 10 deg eccentricity, it was displaced up to ± 0.7 deg for all separations. Eccentric viewing was achieved by having the observer fixate a line placed an appropriate distance from the stimuli. Two observers were tested at each eccentricity.

Results and discussion

Data obtained with fovea-centered stimuli, replicating the standard result, are shown in Fig. 3. The data from each observer were fitted with straight lines on log–log coordinates using a program that weighted each threshold by its inverse variance and minimized χ^2. Slopes for the data of the two observers were 0.9 ± 0.1 and 0.7 ± 0.2 with χ^2 (6 d.f.) of 8.7 and 33.5, respectively. The slope obtained for observer AM is somewhat shallow and has a larger error primarily because the relatively large error bar

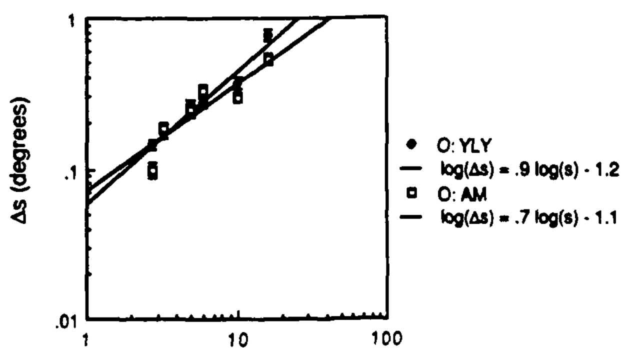

Fig. 3. Separation discrimination thresholds for fovea-centered stimuli plotted as a function of separation on log–log axes for observers YLY and AM. Targets used were rectangles 32 min arc long and 4 min arc tall. Exposure duration was 150 msec. The slopes of the best-fitting lines were 0.9 for observer YLY and 0.7 for observer AM, which follow Weber's law behavior closely.

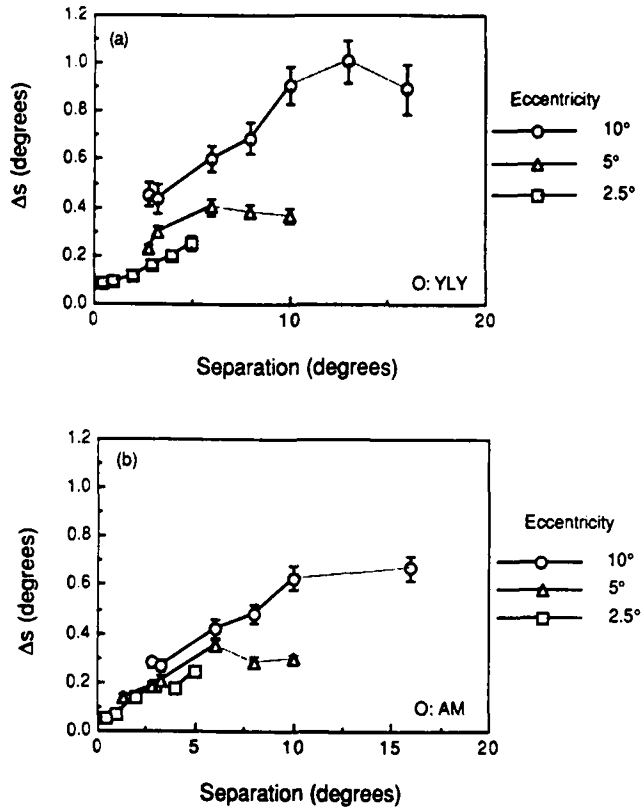

Fig. 4. Separation discrimination thresholds plotted as a function of separation at eccentricities of 2.5, 5 and 10 deg for observers YLY (a) and AM (b). Targets used were rectangles 32 min arc long and 4 min arc tall, placed on isoeccentric arcs with a radius equal to the appropriate eccentricity. Exposure was 150 msec. For both observers, thresholds depend on separation for separations smaller than 5 deg. However, for separations larger than 6 deg at 5 deg eccentricity, and larger than 10 deg at 10 deg eccentricity, threshold becomes a constant function of separation, depending only on eccentricity (stippled connections).

for the smallest separation diminished its contribution to the slope. (A line drawn by eye has a steeper slope.) The other observer was able to replicate the classical result under our stimulus conditions. We conclude that stimulus conditions are within the standard range. Subsequent comparison of our results with data from another laboratory supports this conclusion.

Data obtained with stimuli presented on isoeccentric arcs are shown in Fig. 4. For separations less than about 6 deg at all eccentricities, and for separations less than 10 deg at 10 deg eccentricity the thresholds increased markedly with separation under these isoeccentric conditions. Slopes of 0.5–0.7 on log–log axes were obtained for data in these ranges. The individual slopes are shown in Table 1. These values are similar to the slopes of 0.6–0.7 on log–log axes obtained with 3-dot bisection for eccentricities of 0–10 deg (Yap, Levi & Klein, 1987). Separation was not the only important factor in this separation-dependent region; eccentricity also had a small but significant effect. These results are consistent with those for 3-dot bisection (*ibid.*), and 2-dot separation discrimination for a range of smaller separations (Yap et al., 1989) and with our finding, reported above, that eccentricity had a small effect over a wide range of separations.

For separations larger than 6 deg at 5 deg eccentricity and larger than 10 deg at 10 deg eccentricity, the thresholds lost their dependence on separation, as evidenced by the flattening of the curves. In this separation-independent region, eccentricity had a much larger effect than it had in the separation-dependent region,

Table 1

	Slopes on log-log axes		
Eccentricity	O:PA	O:AM	O:YLY
2.5 deg	0.64 ± 0.07	0.69 ± 0.05	0.50 ± 0.08
5.0 deg		0.65 ± 0.09	0.69 ± 0.20
10.0 deg		0.64 ± 0.07	0.55 ± 0.10

i.e. thresholds for a given separation within this region increased more with increasing eccentricity than did thresholds within the separation-dependent region.

We know that the flattening was not caused by edge effects because the 5 and 10 deg eccentric data were obtained at the same viewing distance (except for the smallest separation at 5 deg eccentricity), and yet those two curves begin to flatten at quite different separations. It appears that the process underlying separation discrimination thresholds at relatively large separations and eccentricities has characteristics quite different from those of the process underlying separation discrimination thresholds at smaller angles. This could be attributed to a single mechanism, whose properties change, or to two mechanisms, one quite sensitive to separation and only somewhat sensitive to eccentricity, and the other quite sensitive to eccentricity and insensitive to separation.

Our isoeccentric data obtained at 2.5 deg eccentricity differed in shape from our other isoeccentric data and therefore required particular attention. To provide a further check on these results, we obtained data from a third observer, PA. The 2.5 deg eccentricity data for all three observers are shown in Fig. 5. At this eccentricity, the function did not flatten for any of the three observers tested. Its slope did decrease significantly as separation increased for observer PA.

The flattening that occurred in our isoeccentric data is roughly consistent with the results reported by Levi et al. (1988). However, they found no effect of separation on bisection thresholds for separations between 3.5 and 10 deg, except for a decrease in threshold at 10 deg separation. There are significant differences between the present experiments and the Levi et al. (1988) study that may account for this discrepancy. Most important is the fact that Levi et al. (1988) used a three-dot bisection task in which the eccentricity of the middle dot decreased as the separation increased. They attributed their decrease in threshold at 10 deg separation to the small eccentricity of the middle dot. In general, the effect of increasing separation in their paradigm may have been partly concealed by the opposite effect of decreasing the eccentricity of the middle dot. This suggestion is supported by the finding that when the same observers, observers DL (Levi & Klein, 1990) and YLY (*ibid* and the present study), were used for the two tasks, the threshold versus separation functions began to flatten at a separation of 3.5 deg for the three-dot bisection task and at a separation of 8–18 deg for the two-dot separation discrimination task.

Levi and Klein (1990) have also collected some separation discrimination data on isoeccentric arcs. For comparison we show our data and theirs together in Fig. 6. (The Levi and Klein data were divided by 0.675 to compensate for the fact that they report the 75% level and we report the 84% level on the psychometric function.) The overall agreement between the results from the two laboratories in excellent. At 2.5 deg eccentricity [Fig. 6(a)] the agreement between the data of our three observers and their observer is remarkable up to a separation of 3 deg. For larger separations at this eccentricity, the Levi and Klein data showed a flattening and ours did not. On the other hand, at 5 deg eccentricity [Fig. 6(b)], the data of Levi and

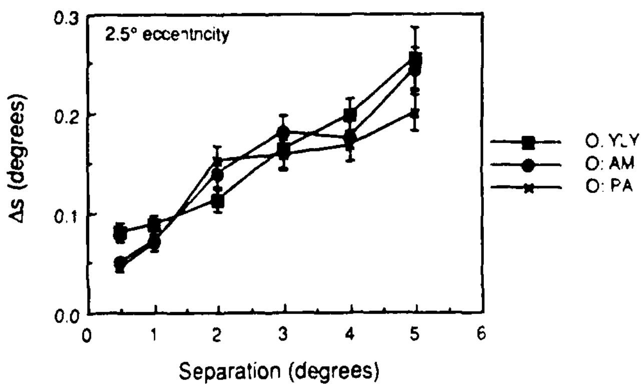

Fig. 5. Separation discrimination thresholds plotted as a function of separation at an eccentricity of 2.5 deg for observers YLY, AM and PA. Targets used were rectangles 32 min arc long and 4 min arc tall, placed on an isoeccentric arc with a radius of 2.5 deg. Thresholds increase with increasing separation for all separations, although the slope decreases significantly for separations greater than 2 deg for observer PA.

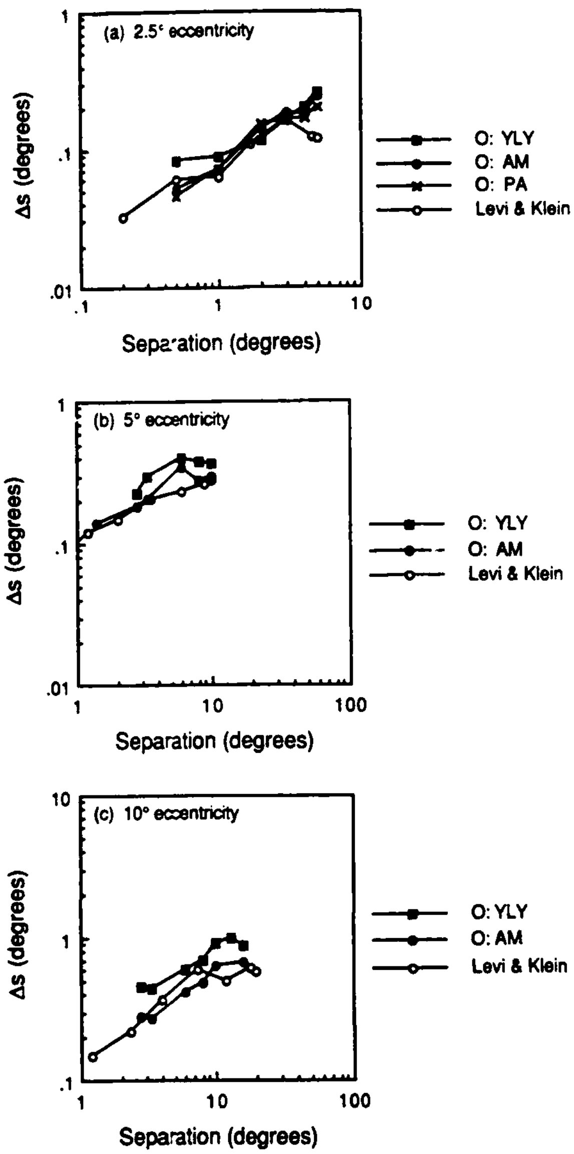

Fig. 6. Separation discrimination thresholds obtained with isoeccentric targets plotted on log–log axes as a function of separation at an eccentricity of 2.5 (a), 5 (b) and 10 deg (c) for observers YLY, AM and PA and observer DL from Levi and Klein (1990). The Levi and Klein data, which were determined at the 75% correct level, have been divided by 0.675, to allow comparisons to be made at an 84% correct level. The standard errors (approx. 10% of the thresholds) have not been shown for the sake of clarity. At 2.5 deg eccentricity, the functions of our three observers did not flatten whereas the function for observer DL did, while at 5 deg eccentricity, our data flattened but those of observer DL did not. At 10 deg eccentricity, both sets of data show a range of separations where the thresholds are independent of separation, but the ranges differ somewhat.

Klein increased monotonically with separation whereas our data showed an obvious flattening for separations larger than 6 deg. At 10 deg eccentricity [Fig. 6(c)], both sets of data flattened at large separations, although the data of Levi and Klein began to flatten at a slightly smaller separation. It is possible that the flattening at 2.5 or 5 deg is not robust because there are two competing mechanisms available at these eccentricities, one separation-dependent and the other separation-independent. The data from experiment 1, which showed weak eccentricity effects at small eccentricities, are consistent with the idea that for small eccentricities, even fovea-centered stimuli may be processed by the separation-dependent mechanism. We conclude that, at all eccentricities tested, separation discrimination thresholds depend primarily on separation when the separation is small (separation ⩽ eccentricity), and can be completely independent of separation when the separation is large, particularly if the eccentricity is also large.

EXPOSURE DURATION EFFECTS

Introduction and methods

The data shown in Figs 1 and 2 suggest that the effect of eccentricity may depend on the spatial or temporal characteristics of the targets, and the strength of this dependence may vary with the separation used. To investigate this hypothesis, we conducted further tests of the effects of these parameters.

For fovea-centered stimuli, the slope of the Weber function for separation depends on exposure duration (Burbeck, 1986; Yap et al., 1987). The threshold at small separations is higher for a 100-msec exposure duration than for a 500-msec or 1-sec duration whereas the threshold at large separations is unaffected by these changes in exposure duration. Thus, the slope is shallower for brief durations than for long ones. To understand more about the temporal factors contributing to the slope of the Weber function for separation, we measured separation discrimination thresholds at an eccentricity of 10 deg using two exposure durations and a range of separations. For separations larger than 1 deg (observer JGP) and larger than 0.5 deg (observer CAB), the targets were the same as in the first experiment (bars 1.3 × 1.1 deg). For the smaller separations, the targets were lines 0.017 × 1.1 deg.

Results

Data from this experiment are shown in Fig. 7. For observer CAB, there was a small effect of exposure duration when the lines were used at separations of 0.5 and 0.8 deg.

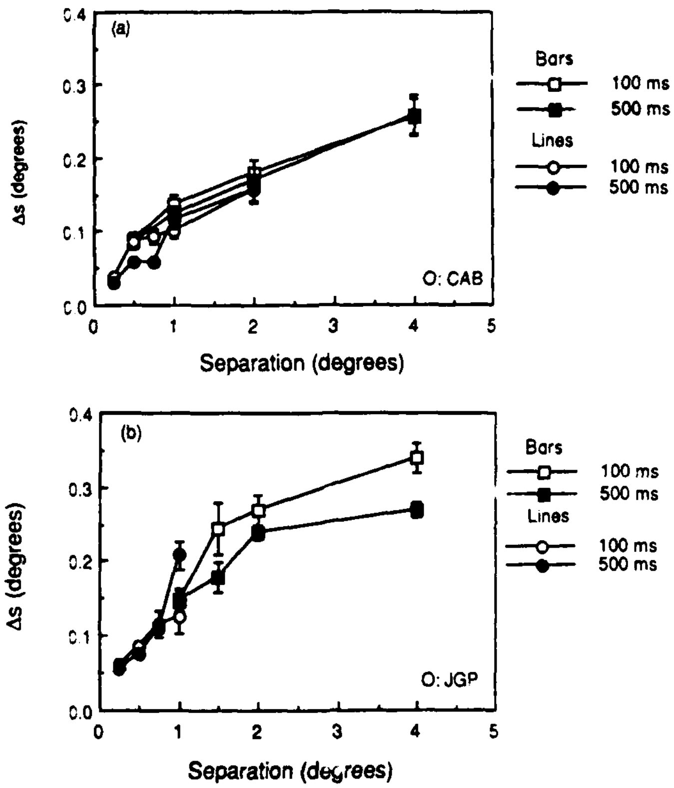

Fig. 7. Separation discrimination thresholds plotted as a function of separation for exposure durations of 100 and 500 msec at an eccentricity of 10 deg for observers CAB (a) and JGP (b). Targets used were bars, 1.3 × 1.1 deg, or lines 0.017 × 1.1 deg. Observer CAB did not show any significant difference between the two exposure durations. Although observer JGP obtained better thresholds in general with a 500-msec exposure than with a 100-msec exposure, he showed a flatter slope with the 500-msec than with the 100-msec exposure.

Otherwise there was no significant effect of exposure duration. Although the performance of observer JGP improved with increasing duration at large separations, the 500-msec function was actually shallower than the 100-msec function. We have no explanation for this effect. Yap et al. (1987) also found a smaller effect of duration at 10 deg than at 0 deg eccentricity for relatively small separations in the three-dot bisection task. The effect was the same for all separations tested at 10 deg but decreased with increasing separation at the fovea. The difference between our present results and the results of Yap et al. (1987) may reflect a difference in approach: whether the observer takes time to ponder over the decision. We have noticed that observers show much less dependence on duration if they pause before deciding rather than responding immediately.

In general, we found that at 10 deg eccentricity, exposure duration had only a small effect on the slope of the Weber function for separation discrimination for either observer. For fovea-centered targets, duration affects the slope only at separations <20 min arc (Burbeck, 1986). Thus, exposure duration does not appear to be a major factor controlling the slope of the Weber function, provided spectrally broadband, high-contrast targets are used.

TARGET SIZE

Introduction and methods

We now turn to the spatial domain to determine whether target size is an important contributor to the Weber function for separation discrimination. We used lines that were 4 min arc wide and varied the length from 1 to 120 min arc. To avoid confounding eccentricity effects with length effects, the target length was extended in the direction away from the fovea. The eccentricity that is referred to in the figures is that of the least eccentric end of the targets. Exposure duration was 150 msec. All other details of the experiment were unchanged.

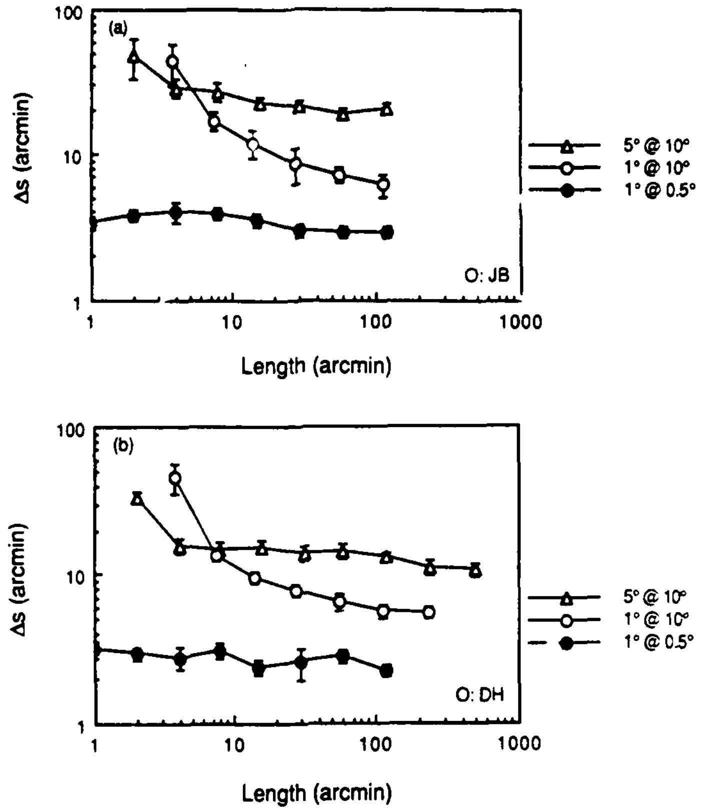

Fig. 8. Separation discrimination thresholds plotted as a function of target length for targets with a height of 4 min arc for a separation of 1 deg at 0.5 deg and 10 deg eccentricity and for a separation at 5 deg at 10 deg eccentricity for observers JB (a) and DH (b). Exposure duration was 150 msec. Thresholds improved sharply with increasing target length for the separation of 1 deg at 10 deg but slightly or not at all for the separation of 1 deg at 0.5 deg eccentricity and the separation of 5 deg at 10 deg eccentricity.

Results and discussion

Figure 8 shows the effect of length on separation discrimination thresholds for a 1 deg separation at 0.5 and 10 deg eccentricity and for a 5 deg separation at 10 deg eccentricity. For the 1 deg separation, there was an interaction between the length effect and the eccentricity. Increasing length improved thresholds significantly at 10 deg eccentricity but had no effect at 0.5 deg eccentricity. Line length also had a significant effect on threshold for a 5 deg separation at 10 deg eccentricity, but the effect was smaller than for the 1 deg separation at this eccentricity. The data suggest that the size of the separation relative to the eccentricity is an important factor in the length effect. In general, line length is a more important factor when the separation is small relative to the eccentricity.

The results of these line-length experiments have implications for the primary focus of this study, namely the roles of eccentricity and separation in the Weber function for separation discrimination. In the experiments on the effects of eccentricity for fixed separation stimuli, we found pronounced eccentricity effects in the 15–30 deg eccentricity range. The slope of the function was steeper with small targets (compare Figs 1 and 2), and with a small separation [compare Figs 2(a) and (b)]. This dependence on target size and separation, together with the results of the line-length experiments showing an interaction between separation and eccentricity, suggests that even the large targets may not have been large enough at 15–30 deg eccentricity. Thus, the eccentricity effects shown in Fig. 1 may include length effects.

The line-length data confirm that the lines used in our isoeccentric study were long enough that length was not a limiting factor. The study was limited to eccentricities $\leqslant 10$ deg.

The problem of how to scale targets appropriately for positional tasks has received much attention in recent years (Levi, Klein & Aitsebaomo, 1985; Watson, 1987; Virsu, Nasanen & Osmoviita, 1987; Yap et al., 1987; Toet, Snippe & Koenderink, 1988) following the demonstration that contrast sensitivity

functions can be made to have the same peak sensitivity and shape in the periphery as in the fovea if the target size is scaled to ganglion cell density (Koenderink et al., 1978; Rovamo et al., 1978). The results of our experiments indicate that scaling the targets with eccentricity may not always be important for positional tasks because the effect of target size at a given eccentricity depends on the separation being tested.

Levi, Klein and Yap (1987) found that for a separation of 0.2 deg at 2.5 deg eccentricity, three-dot bisection and two-dot separation discrimination thresholds are reduced when more stimulus samples are provided. Our line-length results indicate that such improvement occurs only when the separation is small relative to the eccentricity. When it is relatively large, threshold is independent of line length. In general, the line length results indicate that the slope of the Weber function depends on the target size only when the separation is small relative to the eccentricity.

DISCUSSION

The data reported here suggest that there may be two ways to make spatial interval discriminations. When the separation is less than the target eccentricity, the discrimination process depends primarily on target separation and secondarily on eccentricity. When the separation is larger, the process depends primarily (perhaps exclusively) on target eccentricity. What is the nature of these processes? Levi et al. (1988) and Klein and Levi (1987) attribute the small-separation data to the responses of local spatial filters, but there are data to suggest that this explanation is not adequate. The separation-dependent region probably includes all very small separations, certainly all those that fall within the fovea itself, but a simple local-spatial-filter model cannot account for the failure of extraneous flanking lines to affect thresholds for such small separations (Morgan & Ward, 1985). Furthermore, a local-spatial-filter model cannot account for the fact that separation discrimination thresholds are largely unaffected by the spatial frequency content of the individual targets (Burbeck, 1987, 1988; Toet et al., 1987; Toet & Koenderink, 1988). Finally, the local-spatial-filters model does not accurately account for the increase in threshold with separation. For isoeccentric targets, threshold increased approximately as $s^{0.65}$, where s was the mean target separation. A filter model in which error scales with receptive field size predicts that the threshold will increase as s^1.

To deal with some of the problems posed by local-spatial-filter models, Morgan and Regan (1987) have proposed an alternative scheme. They suggest that there is "a plurality of coincidence detectors with different receptive field separations, and two-line interval discrimination depends on the relative activity of the different coincidence detectors." This hypothesis is, or can be readily made consistent with the insensitivity of separation discrimination thresholds to the contrast and spatial frequency content of the targets, but it requires a large number of units, each dedicated to a single task. Also, the hypothesis provides no natural way to account for the increase in threshold with increasing target separation, an especially serious drawback.

We suggest the following alternative explanation for thresholds in the separation-dependent region. A plausible method for calculating separations between targets is to step from one target to the other, counting the steps as one goes, as proposed in a more general context by Fullerton and Cattell (1892). If each step has equal error and the steps are independent, then the Δs vs s function will have a slope of 0.5 on log–log scales. Our data are clearly steeper than that. However, if the steps are not independent but positively correlated, the slope will be larger than 0.5. If the steps are perfectly correlated, the slope will be 1.0. If there is some correlation, the slope will lie between 0.5 and 1.0 (Laming, 1986), as we find. In this context, a slope of 0.65 is consistent with a model in which the errors in the individual steps are slightly correlated.

The step-increment approach has physiological plausibility. It has been rejected in the past because it yields too low a slope, unless one assumes nearly perfect correlation between the errors, which is physiologically implausible. The smaller slopes obtained with the isoeccentric targets make this approach worth reconsidering. Although other models could also be compatible with these new data, it seems worth noting that the incremental step is again viable.

We now consider the separation-independent region. Levi et al. (1988) have proposed the name "cortical ruler" for the separation-independent mechanism. While this name is in keeping with a mechanism that depends on the eccentricity of the targets, it seems misleading because the cortical distance between

the targets does not convey the necessary information. For example, the perceived separation does not decrease with increasing eccentricity (e.g. Schneider, Ehrlich, Stein, Flaum & Mangel, 1978) at the rate predicted by cortical magnification.

Another candidate mechanism is Morgan and Regan's (1987) coincidence-detector model. It is better able to account for the data in this region than in the small-separation region because this model has no natural dependence on separation. However, the requirement that there be many dedicated units continues to pose a problem. Furthermore, the finding that eccentricity plays a larger role in the separation-independent region than in the separation-dependent region is not consistent with this model in its present form. The small effect of eccentricity in the separation-dependent region can be accounted for by an increase in the uncertainty of the local target position with increasing eccentricity. To account for the larger effect of eccentricity in the separation-independent region, an additional eccentricity-dependent source of noise appears to be necessary. In Morgan and Regan's coincidence-detector model, one would have to assume that the noise of the coincidence detectors themselves increased significantly with eccentricity.

We propose an alternative mechanism for the separation-independent region, based on the idea that for relatively large separations, the best information about target separation may be contained in a fovea-centered polar representation. In such a representation, the separation between targets on an isoeccentric arc is represented by an angle. The accuracy with which an angle is encoded depends exclusively on the eccentricity of the targets. As eccentricity increases, the positions of the individual targets are known with less accuracy. Moreover, as eccentricity increases, the distance between the targets and the fovea increases, creating a second eccentricity-dependent source of noise. If the accuracy with which two angles can be discriminated depends primarily on the accuracy with which each angle is represented, then the discrimination threshold would be independent of separation, but would depend heavily on eccentricity. Thus, this model can account for the fact that eccentricity plays a larger role in the separation-independent region than in the separation-dependent region. In the separation-dependent region, thresholds are elevated because the local positional information is degraded. In the separation-independent region, thresholds are further degraded because the increased distance to the fovea degrades the quality of information in the fovea-centered polar representation. A problem with this model is that it does not apply to the condition in which the targets are centered about the fovea. In that case, the observer must judge the distances to the targets.

Although we were unable to invent a mechanism within this scheme to predict when the transition between the separation-dependent and the separation-independent regions should occur, we find it interesting that the transition occurs at a constant angle in the polar-coordinate representation. Our data show a transition at about 50–60 deg for separation discrimination. The data of Levi and Klein (1990) show a transition at about 30–40 deg for bisection. Thus, the model at least adds parsimony to the description of the data. It also suggests that there may be a connection between the representation used to discriminate between large separations and the representation used to direct saccades, which presumably is also fovea-centered.

The possibility that there are two qualitatively different mechanisms underlying separation-discrimination thresholds requires that we reexamine many conclusions that have been drawn about the separation-discrimination mechanism. For example, the fact that separation-discrimination thresholds are unaffected by large changes in the spatial-frequency content of the targets (Toet et al., 1987; Toet & Koenderink, 1988; Burbeck, 1987, 1988) except when the duration is short (Burbeck, 1986; Burbeck & Yap, 1990) has served as an argument against the local-spatial-filters model of separation discrimination. However, most of the targets used in those studies were fovea-centered and many had separations that were large enough to place the targets off the fovea. Under those conditions, one cannot be certain that the stimuli lie in the separation-dependent region. Thus these studies may actually be investigations of a separation-independent process. The possibility that there are two mechanisms of separation discrimination may require the reanalysis of many such results.

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Appendix B

SPATIAL CONTRAST INTEGRATION AND THE LENGTH EFFECT IN SEPARATION DISCRIMINATION

SPATIAL CONTRAST INTEGRATION AND THE LENGTH EFFECT IN SEPARATION DISCRIMINATION

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Abstract

Improvement in separation discrimination resulting from elongation of a stimulus has been related to an increase in the number of samples in the stimulus. We investigated to what extent contrast effects contribute to this effect. Separation discrimination thresholds measured as a function of length were compared to separation discrimination thresholds measured as a function of height. The threshold versus length function was measured for targets in which stimulus strength was increased with taller, higher contrast and/or longer exposed targets. Two target separations were used in the fovea and at 10 deg eccentricity. When the targets were small, contrast effects played an important role in the length effect, particularly for the smaller separation. However, a residual improvement with increasing target length could still be obtained for the smaller separation at each eccentricity. There was little or no contrast-independent length effect for the larger separation at either eccentricity. These results are discussed with respect to the spatial properties of local spatial filters.

Key Words

Separation Discrimination, Length Effect, Spatial Integration, Localization, Contrast Integration.

LENGTH EFFECT IN SEPARATION DISCRIMINATION

1. Introduction

The precision with which the relative position of lines can be judged, e.g., in separation discrimination or bisection, has been shown to improve as the lines are made longer (Andrews, Webb and Miller, 1973; Westheimer and McKee, 1977; Andrews and Miller, 1978; and Burbeck and Yap, in press). For high contrast stimuli comprised of discrete spatial samples, the improvement corresponds to an increase in the number of independent samples rather than an increase in the total length of the samples, (Levi, Klein and Yap, 1987). The axis along which the samples are added is important: additional stimulus samples lower the threshold when placed along an axis orthogonal to the axis of discrimination but not when placed along an axis parallel to the axis of discrimination, indicating that the improvement obtained by adding length to samples is not caused by spatial contrast integration. Levi et al. also found that the rate of improvement increases with increasing eccentricity for these high-contrast discrete-sample stimuli.

The dependence of the length effect on eccentricity has also been reported for lower contrast stimuli (Burbeck and Yap, in press). Not only does the length effect depend on the eccentricity of the targets, it also depends on the separation, as shown in Fig. 1 (Burbeck and Yap, in press). For a given separation, the length effect is stronger in the periphery than in the fovea and for targets presented at the same eccentricity, it is stronger for a small than for a large separation. If small separations are encoded by higher spatial frequency filters than are large separations, as is consistent with most current models, then part of the length effect may be attributable to spatial contrast integration. Contrast sensitivity decreases with increasing spatial frequency and eccentricity (Hilz and Cavonius, 1974; Koenderink, Bouman, Bueno de Mesquita, and Slappendel, 1978a,b; Rovamo, Virsu and Nasanen, 1978) and the higher spatial frequency filters may be operating near detection threshold. Thus increasing the stimulus strength, e.g., by increasing target length,

should have a greater effect when the separation is small or when the eccentricity is large. The data shown in Fig. 1 are consistent with this hypothesis.

The present research investigated the extent to which the length effect could be attributed to spatial contrast integration. In the first two experiments, the effect of increasing length was compared to the effect of increasing stimulus strength. In the third experiment, the effect of length was determined under conditions in which the effect of contrast was neutralized. The remaining experiments were directed toward measuring the length effect for a small separation in the fovea, and toward characterizing the residual contrast-independent length effect for each separation and eccentricity. These results are discussed with respect to the spatial properties of local spatial filters.

2. Changing the Axis of Elongation

If increasing the length improves thresholds by increasing the effective stimulus contrast, as opposed to increasing the number of samples, then increasing the stimulus strength in other ways should also produce an improvement in threshold. For example, making the lines taller in a vertical separation discrimination task i.e., extending the targets along the axis of discrimination, should produce the same effect on threshold as increasing length, particularly for smaller targets which are closer to their detection threshold than are larger targets. Larger targets may not benefit as much from an increase in the effective contrast because they are well above the detection threshold. However, the separation discrimination thresholds for larger targets may be lowered by an increase in the number of stimulus samples. To investigate the extent to which the length effect can be attributable to spatial contrast integration, the dependence of separation-discrimination thresholds on height was measured for short and long targets.

2.1 Methods

Separation discrimination thresholds were measured as a function of bar height for a 1 deg separation at 10 deg eccentricity. Fig. 2 shows the spatial configuration of the stimuli, which consisted of two horizontal bar targets separated vertically. Target contrast ((Lmax-Lbkg)/Lbkg) was 90% on a background of 90 cd/m2 (Conrac 2400, 19 in diagonal, 60 HZ noninterlaced frames rate, 512 by 512 pixels). The 4 or 30 minarc targets were presented for 150 ms. Target height was increased symmetrically about the center of each bar while holding constant the 1 deg average center-to-center separation. To prevent the observer from using the vertical distance of the stimulus to the screen edges as a cue, the stimuli were displaced from trial to trial by a random vertical distance in the range ±9 minarc. To avoid artifacts caused by proximity to the edges of the screen, the targets were presented in the center of the screen. The observers fixated a spot 10 deg to the left of the targets. The reported eccentricity of the targets corresponded to the visual angle between the fovea and the midpoint of the closest vertical edge of each target. Viewing distance was 2.1 m and the room was otherwise dark.

The task of the observer was to decide whether the separation presented on each trial was larger or smaller than the average separation. Fourteen separations were presented: $S \pm n\Delta S$, where n is an integer from 1 to 7. ΔS was determined from pilot runs. Auditory feedback of the correct answer was provided after each trial. Observers learned to do the task quickly and consistently. Each run was preceded by a set of 14 practice trials. The order of runs was nonsystematic.

Threshold estimates for individual runs were calculated at the 84% correct level by standard probit analysis techniques (Finney, 1971). Geometric means were obtained by combining individual threshold estimates weighted by their inverse variances. Each mean threshold estimate was based on at least 420 trials. The standard errors shown include both within- and between-session variability (see Klein and Levi, 1987).

Two observers, JB and DH, were used in this experiment; both viewed with the right eye. A third observer, TRM who served in subsequent experiments, used his left eye. All observers had normal or corrected-to-normal vision.

2.2 Results

Fig. 3 shows thresholds plotted as a function of increasing height for a constant 4 minarc length and, for comparison, the data of the same observers from Fig. 1 in which the length was increased for a constant 4 minarc height. Up to 15 or 20 minarc, increasing target height and increasing target length produced a very similar improvement in the separation discrimination thresholds. Observer DH showed slightly lower thresholds for targets of increasing height compared to targets of increasing length. It is likely that this small difference is due to practice as the threshold by height function was measured after the threshold by length function. For small targets, the similarity in the length and height effects is compatible with the hypothesis that the effect of increasing length is to increase stimulus strength. This result differs from that of Levi et al.(1987), who found that additional height samples do not improve separation-discrimination thresholds whereas additional length samples do. This difference is discussed below.

Because the 1 deg separation did not permit further increases in bar height without overly reducing the edge-to-edge separation of the targets, the effect of stimulus strength for larger targets was investigated by increasing the height of longer bar targets. To compare the effects of increasing the length versus the height for larger targets, Fig. 4 shows separation-discrimination thresholds plotted as a function of area, for one observer. Thresholds for targets with a constant 30 minarc length improved little if any with increasing area, unlike the thresholds for targets with a constant 4 minarc length or height. Thus for long targets, increasing the height does not improve thresholds but increasing the length does, despite the fact that the target area increases by the same amount in both cases. This finding suggests that the length effect at longer lengths cannot not be attributed to

contrast integration. However, the finding that separation discrimination for larger targets benefits from increasing target length is at least qualitatively consistent with Levi's result that increasing the number of high contrast stimulus samples along an axis orthogonal to the axis of discrimination lowers separation discrimination and bisection thresholds.

3. Increasing Stimulus Strength

The results of the first experiment suggest that thresholds decrease with increasing length for short targets because of spatial contrast integration. For longer targets, spatial contrast integration was of little importance but thresholds could still be lowered by the availability of additional separation samples. However, the effects of bar height were measured for only two target lengths, 4 and 30 minarc. To obtain a more detailed description of how a threshold depends on stimulus strength, separation discrimination thresholds were measured as a function of length by using targets which were taller and of higher contrast than in the previous experiment.

3.1. Methods

Separation discrimination thresholds were measured as a function of bar length with a target height of 14 minarc for observers DH and TRM. As in the previous experiment, target separation was 1 deg at 10 deg eccentricity. Separation discrimination were also measured for targets of this height with the contrast increased well above the original 90% by lowering the background luminance to 4 cd/m2. Dimming the background from 90 to 4 cd/m2 increased the target contrast by approximately 50x. All other experimental details remained the same.

3.2 Results

Fig. 5 shows the changes in the length effect for the 1 deg separation at 10 deg eccentricity resulting from the use of taller targets with and without the higher contrast. Use of the 14 minarc target

height alone produced the greatest drop in thresholds for the shortest lengths (lengths less than 8 minarc) and had less effect as target length increased. Raising the target contrast by a factor of 50 for these taller targets brought a small additional change at all lengths for observer DH and at lengths of 8 minarc or less for observer TRM. A residual length effect remained for both observers. These results confirm that increasing length increases the effective stimulus contrast, particularly for small targets, but length also lowers threshold by some other means.

4. Eliminating Contrast Effects

Although the results of the previous experiments show that the effect of length is largely one of increasing the effective contrast of the stimulus, a residual length effect could still be obtained even when the effect of stimulus strength should have been neutralized by the use of taller and higher-contrast targets. This suggests that the residual effect is independent of the contrast of the targets. To test this hypothesis, performance of separation discrimination was measured as a function of target length by using a target contrast set to a fixed multiple of the contrast detection threshold.

4.1 Methods

Contrast detection thresholds were measured at 10 deg eccentricity using the method of constant stimuli with a 2-alternative forced-choice paradigm. Target heights of 4 and 14 minarc were used. The background luminance was 90 cd/m2. The task of the observer was to report whether the target appeared in the upper or lower field; the locations were fixed and separated by 1 deg. The target contrast in each trial was randomly chosen from a set of 7 contrasts, $C + n\Delta C$, where n is an integer from 0 to 6. The values of the set were determined from pilot runs. Feedback of the correct answer was provided after each trial. Each run was preceded by a set of 14 practice trials; the order of runs was nonsystematic.

Separation discrimination thresholds were measured as a function of bar length for 14 minarc tall bars separated by 1 deg at 10 deg eccentricity with the contrast thresholds set to 1.5x the observer's detection threshold at each target length. All other experimental details remained the same as previously.

4.2 Results

Fig. 6 shows the contrast-detection thresholds at 10 deg eccentricity using bars with a 4 or 14 minarc height for observer TRM. The contrast-detection thresholds for both target heights improved steeply along an approximately straight line as bar length increased up to the longest length for the 4 minarc height and up to a length of 100 minarc for the 14 minarc height. This linear pattern of contrast dependence on length is different from the decelerating curve of dependence for the separation discrimination thresholds. The difference between the shapes of these two types of functions provides another indication that signal strength is not the sole contributor to the length effect for separation discrimination.

For the 4 minarc target height, contrast thresholds were higher than 50% for target lengths of less than 15 minarc, approaching the target contrast of 90% used in the first experiment. Thus it is plausible that the main effect of length for small targets is to increase their effective contrast through spatial contrast integration. The finding of the first experiment, that the effect of height and length is similar for small targets, is also consistent with this hypothesis. Although Levi et al. (1987) found that adding height samples did not result in an effect, their result is not incompatible with this hypothesis since they used targets of high contrast (at least 5-6 times contrast threshold) which are unlikely to produce further spatial contrast integration (Burbeck, 1986, 1987; and Morgan and Regan, 1987).

Because the high contrast thresholds for the shorter lengths made it impractical to use the target height of 4 minarc for the constant-effective-contrast study, separation discrimination thresholds

were measured only for the 14 minarc targets. Fig. 7 shows the threshold versus length function for separation discrimination, using bar targets with a height of 14 minarc and contrast set to 1.5x the detection threshold at each length. The separation discrimination thresholds obtained with targets of constant multiple-of-threshold-contrast increased with target length even though the detectability of the targets was kept constant. Also shown in Fig. 7 for comparison is the threshold versus length function for high contrast targets of the same height. The function for the constant multiple-of-threshold-contrast targets closely paralleled the function obtained with the high contrast targets, showing that the residual length effect is independent of contrast. Thresholds for the high contrast condition were only 0.2 to 0.3 log units lower on average than the thresholds for the 1.5x-detection-threshold condition, despite the large difference in target contrasts for the two conditions. These results are consistent with previous reports that contrast plays a small role in separation discrimination for targets, once contrast exceeds two to three times the contrast detection threshold (Burbeck, 1986, 1987; and Morgan and Regan, 1987).

5. Interactions Between Separation and Eccentricity

The data of Fig. 1 show that at 10 deg eccentricity, length has less effect on separation discrimination thresholds for a 5 deg separation than for a 1 deg separation. Before proceeding to investigate the residual length effect, it seems worthwhile to determine whether the interaction between separation and eccentricity is a general phenomenon that occurs in foveal vision as well as in the peripheral retina. Separation-discrimination thresholds were measured as a function of stimulus length for a small and a relatively large separation across the fovea.

5.1 Methods

Separation-discrimination thresholds were measured as a function of length for fovea-centered separations of 8 minarc and 1 deg. Fig. 2 shows a schematic illustration of the spatial configuration of

the foveal stimuli. The increase in bar length was symmetric about the midpoint of each bar target. No fixation mark was used; the observer simply fixated the center of the screen. To prevent the observer from using the vertical distance of the stimulus to the screen edges as a cue, the stimuli were displaced vertically from trial to trial by a random distance in the range of ±6 minarc for the 8 minarc separation and ±9 minarc for the 1 deg separation. Viewing distance was 10.3 m for the 8 minarc separation and 2.1 m for the 1 deg separation. Line heights of 1 and 4 minarc were used for the 8 minarc and 1 deg separations respectively. All other details were similar to those of the previous experiment.

5.2 Results

Fig. 8 shows the results of these experiments plotted with the foveal and 10 deg data obtained previously. The length effect depended on the separation of the targets across the fovea as much as it did in the periphery. Separation-discrimination thresholds for the fovea-centered stimuli improved more with increasing length for the smaller separation (8 minarc), than for the larger separation (1 deg). However, a shorter bar height (1 minarc) was used for the 8 minarc separation than for the 1 deg separation (4 minarc); thus the difference between the strength of the length effects might have been due to the difference in the line heights. To test this possibility, data were obtained for the fovea-centered 1 deg separation with the height of the target lines reduced from 4 to 1 minarc for observer TRM. Thresholds were not affected by this change.

6. Separation-Eccentricity Interaction and the Contrast-Independent Length Effect

The results of the last experiment showed that the length effect depended as much on separation across the fovea as it did in the periphery. In addition, previous experiments reveal that although the primary effect of length is to increase the effective contrast of the targets, a residual effect of

length could be obtained in the absence of contrast effects. Does the contrast-independent residual length effect also depend on the separation and eccentricity of the targets? To answer this question, the length effect was measured by using targets of increased strength for the small foveal separation and the large peripheral separation.

6.1 Methods

Separation-discrimination thresholds were measured as a function of stimulus length with increased target height, contrast, and/or exposure duration for observers DH, JB and TRM. For the separation of 5 deg at 10 deg eccentricity, the length effect was determined for a height of 15 minarc for observer JB and 30 minarc for observer DH. The background luminance was 90 cd/m2. A viewing distance of 1 m and a vertical trial-to-trial stimulus displacement in the range ±19 minarc was used (as in Fig. 1).

Since the separation of 8 minarc did not permit the use of taller targets without overly reducing the edge-to-edge target separation, the threshold versus length function was determined by using a long exposure duration (500 ms) for this separation. The longer exposure duration has the effect of preferentially increasing stimulus strength for high spatial frequencies. For comparison, the function was also determined for an increase in stimulus strength obtained by dimming the background to 4 cd/m2. All other details were similar to those of the previous experiment.

6.2 Results

Fig. 9 shows the data obtained with taller targets for the 5 deg separation at 10 deg eccentricity. The increase in target height to 15 or 30 minarc lowered thresholds only for lengths shorter than 3 minarc. The small improvement obtained by increasing stimulus strength was less for the 5 deg separation than for the 1 deg separation at the same eccentricity. In addition, the larger separation

showed little or no residual contrast-independent length effect, unlike the smaller separation which showed a shallow contrast-independent length effect (see Fig. 7).

Fig. 10 shows the data obtained with targets of higher contrast and/or prolonged exposure for the foveal 8 minarc separation. The data show that both exposure duration and target contrast produced a large change on the length effect for the foveal 8 minarc separation. The strongest effect was obtained at the shortest target lengths; these are similar to earlier results for the 1 deg separation at 10 deg eccentricity.

Although the length effect for the 8 minarc separation was not determined with targets of a constant effective contrast, the data suggest that the threshold versus length function for the high-contrast 500 ms-duration targets is representative of a contrast-independent residual length effect. Firstly, the shape of the function is relatively straight. Secondly, the shallow slope of the residual length effect for this condition is similar to the small foveal length effect found with high contrast targets separated by 3 minarc (Westheimer and McKee, (1977). Thus, although it is possible that some contrast effects remain, it appears likely that a contrast-independent length effect exists for the smaller foveal separation but not for the larger foveal separation.

Fig. 11 summarizes all conditions in which the contrast effect may have been eliminated. In each case, the condition with the flattest threshold versus length function has been represented. The contrast-independent length effect was generally much shallower than the overall length effect. For the larger separation at each eccentricity there was little or no effect. It is interesting to note that the contrast-independent length effect for the smaller separation at each eccentricity appeared to have the same slope at both eccentricities and for both observers.

The residual length effect was approximately linear on log-log axes. Thus the longer the target, the greater the increase in the target length that is required to make the same impact. The slopes of the residual length effect in this study were less than -0.2 in every condition. Levi et al. (1987) found slopes of -0.3 and -0.5 on log-log axes for a separation of 3 minarc at the fovea and 12 minarc at

2.5 deg eccentricity respectively when measuring bisection thresholds with multiple discrete 1 minarc-long samples. However, Levi 's slopes are derived from plots of threshold against the number of 1-minarc samples rather than plots of threshold against the overall length subtended by the samples including the interspaces. It may be that the slopes of the length effect obtained in this study would be steeper if they were to reflect the threshold dependence on the number of independent samples rather than the overall length of the bar targets.

Andrews and Miller (1978) found that the threshold versus length function showed a flat slope for short targets and a negative slope for longer targets. They suggest that performance should be independent of stimulus size up to the limits of the receptive field size of a local target detector. The present results did not reveal convincing evidence of this.

7. Summary and Discussion

This study shows that the improvement in the performance of separation discrimination obtained by elongating individual targets is primarily a contrast effect and that for separations that are small relative to the eccentricity, there is also a contrast-independent length effect. The effect of length for small targets could be dramatically altered by increasing the height, contrast and/or exposure duration of the targets, particularly for the smaller separation at each eccentricity. For small targets, the effect of increasing length could be duplicated by increasing height. The finding that contrast detection thresholds for small targets were close to the set contrast of 90% used in most conditions provides further support for the hypothesis that for small targets, the main effect of increasing length is to increase stimulus strength.

For longer lines, increasing the height of the targets did not improve separation-discrimination thresholds whereas increasing the length continued to produce a modest effect. In addition, performance improved with increasing length even when the effective contrast of the targets was kept

constant at 1.5x the observer's detection threshold. These results indicate that length acts to increase the number of stimulus samples when stimulus strength is high.

The length effect was stronger for small compared to large separations across the fovea, similar to previous findings in the periphery. In the absence of contrast effects, a shallow residual length effect was found for the smaller separation at each eccentricity. Little or no contrast-independent length effect was found for the larger separation at each eccentricity.

7.1 Single-Stage Local-Spatial-Filter Models

There is substantial evidence that the first stages of visual processing can be closely approximated by a range of neural filters, each limited to a certain bandwidth in space, orientation and spatial frequency (see DeValois and DeValois, 1988). The first local spatial filter models of separation discrimination and/or bisection predicted positional thresholds based on the contrast-response function of filters tuned to the spatial frequency of the separation between the targets (Wilson and Gelb, 1984; Klein and Levi, 1985). The incorporation of spatial sampling of local spatial filters (as in Wilson and Gelb, 1984) makes single stage filter models compatible with some of the findings of this study. For example, the variation of the contrast-dependent length effect with separation and eccentricity can be attributed to the decrease in contrast sensitivity of local spatial filters with increasing spatial frequency and eccentricity (Hilz and Cavonius, 1974; Koenderink, Bouman, Bueno de Mesquita, and Slappendel, 1978; Rovamo, Virsu and Nasanen, 1978). Similarly, the stronger contrast-independent residual length effect for small separations at each eccentricity can be attributed to a denser sampling of smaller filters. The denser sampling of smaller filters has been shown to follow from the hypothesis that contrast thresholds are scale invariant, e.g. with eccentricity and number of cycles (Koenderink and van Doorn, 1982).

However, other results of the present study cannot easily be explained by single-stage local spatial filter models. One problem lies with the finding that separation discrimination thresholds for small

targets were found to improve in the same way with increasing target height as with increasing target length. The Klein and Levi model would predict that positional thresholds can only benefit from the elongation of targets parallel to the axis of an oriented filter. This is because a filter that responds to the spatial frequency content of the spatial interval, rather than of the individual targets must have both targets within its receptive field. In order that the contrast be spatially integrated as a target is extended, the target must fall within the excitatory zone of a receptive field. Thus extending the targets along an axis parallel to the axis of the receptive field of the filter could result in a heightened contrast response. However, extending the targets along an axis perpendicular to the axis of the receptive field should not produce much effect since such targets would extend into both the inhibitory and excitatory regions of the receptive field. The Wilson and Gelb model may predict some effect of height since it pools the response of the receptive field centered on the stimulus with those of its closest neighboring filters. However, since the centered filter provides the main response to the stimulus, the effect of height should still be reduced in comparison to that of length.

Another problem for single-stage local-spatial-filter models is the finding that the contrast-independent residual length effect was stronger for peripheral targets of a given separation. If the contrast-independent effect results from increasing the number of stimulus samples, the opposite result should have been obtained since the density of spatial filters decreases with increasing eccentricity. To explain the shallower foveal dependence on length samples, Levi et al. (1987) proposed that foveal targets are cortically over sampled relative to peripheral targets; thus additional foveal samples are of little importance. However, this explanation is unable to account for the presence of the contrast-independent residual length effect with the smaller separation across the fovea.

7.2 Two-Stage Models

To better account for a wide range of separation discrimination data, two stages of processing have been postulated: initially the positions of the individual targets are processed by a set of local spatial filters and subsequently the relative separation of the targets is extracted and compared to a referent separation (Watt and Morgan, 1985; Burbeck and Yap, in press).

The properties of the local spatial filters are well known. One way to derive the properties of the second stage mechanism, the separation mechanism, is to attribute to it aspects of separation discrimination performance which cannot be explained using local spatial filters alone. For example, as the separation-discrimination threshold is not affected when the relative contrast of the two targets is randomly perturbed, the separation mechanism can be thought to extract separation independently of contrast (Morgan and Regan, 1987). The lack of contrast integration within the separation mechanism is further indicated by the absence of change in the slope of the threshold versus separation function when target contrast is increased from 1.5 to 10x the detection threshold (Burbeck, 1986). The results of these studies, together with the data from the present study showing that increasing length lowered thresholds in the same way as increasing contrast for small targets, all suggest that integration of signal strength is occurring at the level of the local spatial filters. These results are consistent with neurophysiological evidence indicating that contrast integration occurs mainly at early levels in the visual pathway (Sclar, Maunsell and Lennie, 1990).

Similarly, the finding that the overall length effect depends on the separation and eccentricity of the targets can be attributed to activity at the level of the local spatial filters, if targets that are closely separated relative to the eccentricity are detected by smaller less sensitive filters than targets that are widely spaced relative to the eccentricity. Burbeck (1986) presents evidence that smaller and less sensitive filters are used to detect closely separated fovea-centered targets. Her results show that the effect of exposure duration for small separations can be duplicated for large separations using

high spatial frequency targets. The present study provides support for this hypothesis in the periphery as well as the fovea. The effect of stimulus strength was found to be more pronounced for the smaller separation both at 0 and 10 deg eccentricity. The dependence of this effect on relative rather than absolute separation, since a larger effect was obtained for the 1 deg separation at 10 deg eccentricity than across the fovea, can be linked to the scaling of contrast sensitivity with increasing eccentricity (Koenderink, Bouman, Bueno de Mesquita, and Slappendel, 1978; Rovamo, Virsu and Nasanen, 1978; Swanson and Wilson, 1985). However, the question still remains of why small local filters are not consistently used for large as well as small separations for targets of the same eccentricity. Several studies (Burbeck, 1987; Toet et al., 1987; Toet and Koenderink, 1988) show that separation discrimination thresholds for large separation are little affected by spatial frequency manipulations, thus indicating that the separation mechanism operates well on all sizes of local spatial filters, given adequate signal strength. Burbeck and Yap (1990) argue that the separation mechanism selects information from filters with the strongest reliable signal, usually the larger filters at each eccentricity. Their results show that separation discrimination for a large separation relies on higher spatial frequency information only if the stimulus,a pair of bar targets, is presented in a cluttered environment, i.e., embedded in a set of extraneous parallel bars spaced widely enough not to cause spatial interference or crowding. In an uncluttered environment, performance is not affected when higher spatial frequencies are removed. Together these studies support the idea that for separations that are small relative to the eccentricity, the individual targets are detected by smaller and less sensitive filters.

Can the two-stage model explain how the contrast-independent residual length effect depends on target separation and eccentricity? As in the single-stage filter model, the stronger effect for relatively small separations at each eccentricity may be explained by a denser sampling of smaller filters at each eccentricity. The single-stage filter model fails to explain why the contrast-independent residual length effect is weaker for the fovea-centered 1 deg separation than for the peripheral 1 deg separation and the foveal 8 minarc separation. A two-stage model could account for this result if

the aperture size of the second stage mechanism were to increase with eccentricity for a given separation. This arrangement allows more samples to be picked up in the periphery, where performance is poorer than at the fovea. However, the lack of a contrast-independent length effect for the larger separation at each eccentricity suggests that the larger spatial filters at each eccentricity may be very sparsely sampled with respect to the aperture size of the separation mechanism. A less plausible alternative is that the aperture size of the separation mechanism decreases with increasing separation for any given eccentricity.

7.3 Conclusions

In conclusion, the main effect of length on separation discrimination thresholds was to increase the signal strength through spatial contrast integration. Length also had a small contrast-independent effect, particularly for the relatively small separations at each eccentricity. The results of this study show that spatial integration plays an important role for local spatial filters but is of little importance to higher level separation mechanisms.

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Figure Captions

Fig. 1 Separation-discrimination thresholds plotted as a function of bar length for fovea-centered separation of 1 deg and separations of 1 and 5 deg at 10 deg eccentricity for observers DH (a) and JB (b). At 10 deg eccentricity, thresholds improved more steeply with length for the small separation than for the large separation. For the separation of 1 deg, the length effect was stronger for the targets at 10 than at 0.5 deg eccentricity. Peripheral target length was increased away from the fovea to minimize confounding the effect of length with that of decreasing eccentricity. Where standard errors are not shown in this or the following figures, they are smaller than the size of the symbols. (Reprinted from Burbeck & Yap, in press.)

Fig. 2 Fovea-centered and peripheral stimuli used to measure the effect of target length on performance of separation discrimination. The length and height refer to the horizontal and vertical extents of each target respectively. The stimuli were presented with an abrupt onset and offset for a duration of 150 ms.

Fig. 3 Separation-discrimination thresholds plotted as a function of increasing height for targets of a constant 4 minarc length for observers DH (a) and JB (b). The threshold versus length function for targets of a constant 4 minarc height from Fig. 1 is shown for comparison. Up to 15 or 20 minarc, thresholds improved with increasing height in the same way as as with increasing length.

Fig. 4 Separation-discrimination thresholds plotted as a function of increasing target area with a constant target length of 30 minarc for observer JB. Also shown for comparison are the functions for a constant target length and height of 4 minarc for the same observer. Thresholds for the 30 minarc target length did not improve significantly as the target height was increased. In comparison, thresholds for targets with an equivalent area improved as target length was increased.

Fig. 5 Separation-discrimination thresholds plotted as a function of increasing target length for 4 and 14 minarc target heights for observers DH (a) and TRM (b). Using taller targets of 14 minarc height improved performance for the shorter target lengths. Using a higher target contrast in addition produced a further improvement at all lengths for observer DH, and only at the shorter lengths for observer TRM.

Fig. 6 Contrast-detection thresholds plotted as a function of bar length at 10 deg eccentricity with 4 and 14 minarc target heights for observer TRM. Target locations were 1 deg apart. The contrast discrimination thresholds improved steeply and linearly, with increases in length up to 100 minarc for the 14 minarc height, and with increases beyond 100 minarc for the 4 minarc height.

Fig. 7 Separation-discrimination thresholds plotted as a function of increasing target length for targets with a constant effective contrast, set to 1.5 times observer TRM's detection threshold. Target separation was 1 deg at 10 deg eccentricity. Separation-discrimination thresholds continued to improve with target length despite the lack of change in the effective target contrast. Also shown is the function obtained using targets of enhanced contrast. The two functions paralleled each other closely, indicating that the residual length effect was independent of contrast.

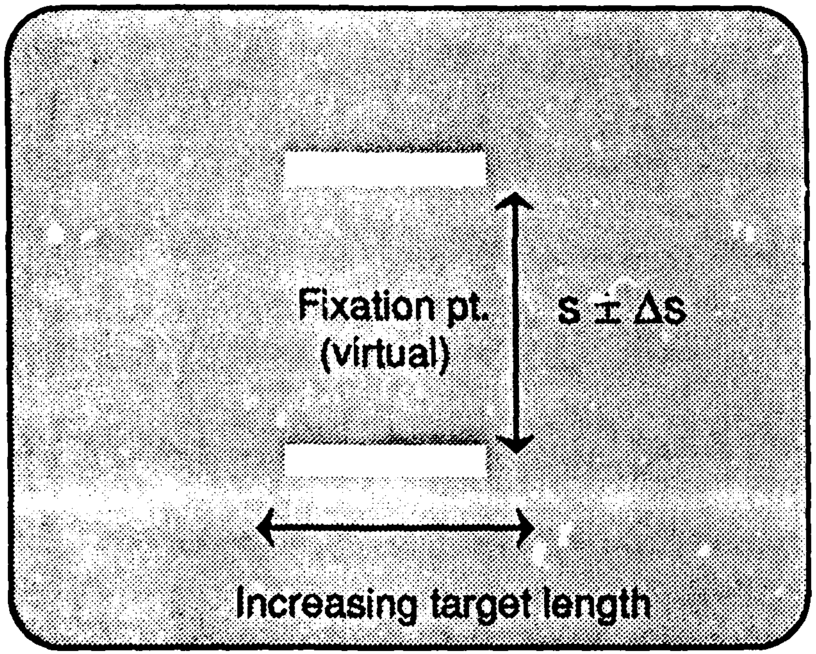
Fig. 8 Separation-discrimination thresholds plotted as a function of target length for fovea-centered separations of 8 minarc and 1 deg and separations of 1 and 5 deg at 10 deg eccentricity for observers DH (a) and TRM (b). Similar to the periphery, the foveal thresholds improved more steeply with length for the smaller separation than for the larger separation. No difference was obtained in the threshold versus length function for the fovea-centered 1 deg separation when the target height was reduced from 4 to 1 minarc.

Fig. 9 Separation-discrimination thresholds plotted as a function of increasing target length for a separation of 5 deg at 10 deg eccentricity using target heights of 4 and 30 minarc for observer DH, and target heights of 4 and 15 minarc for observer JB. A small improvement in performance occurred for lengths shorter than 4 minarc.

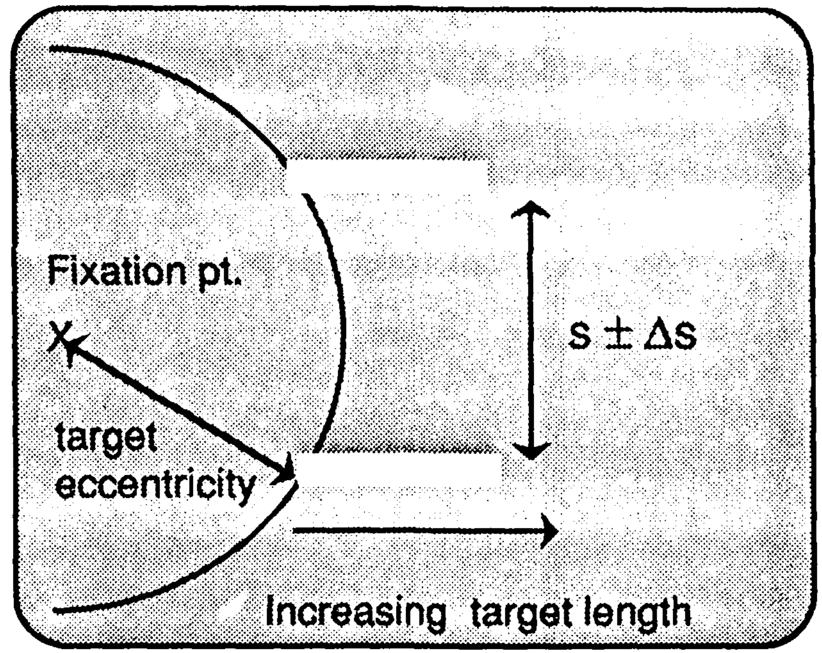
Fig. 10 Separation-discrimination thresholds plotted as a function of increasing target length for a fovea-centered separation of 8 minarc for two exposure durations and two target contrasts, for observers DH and TRM. Target height was 1 minarc. The steepest improvement in the length effect, as the stimulus strength was increased, occurred for targets shorter than 2 or 3 minarc.

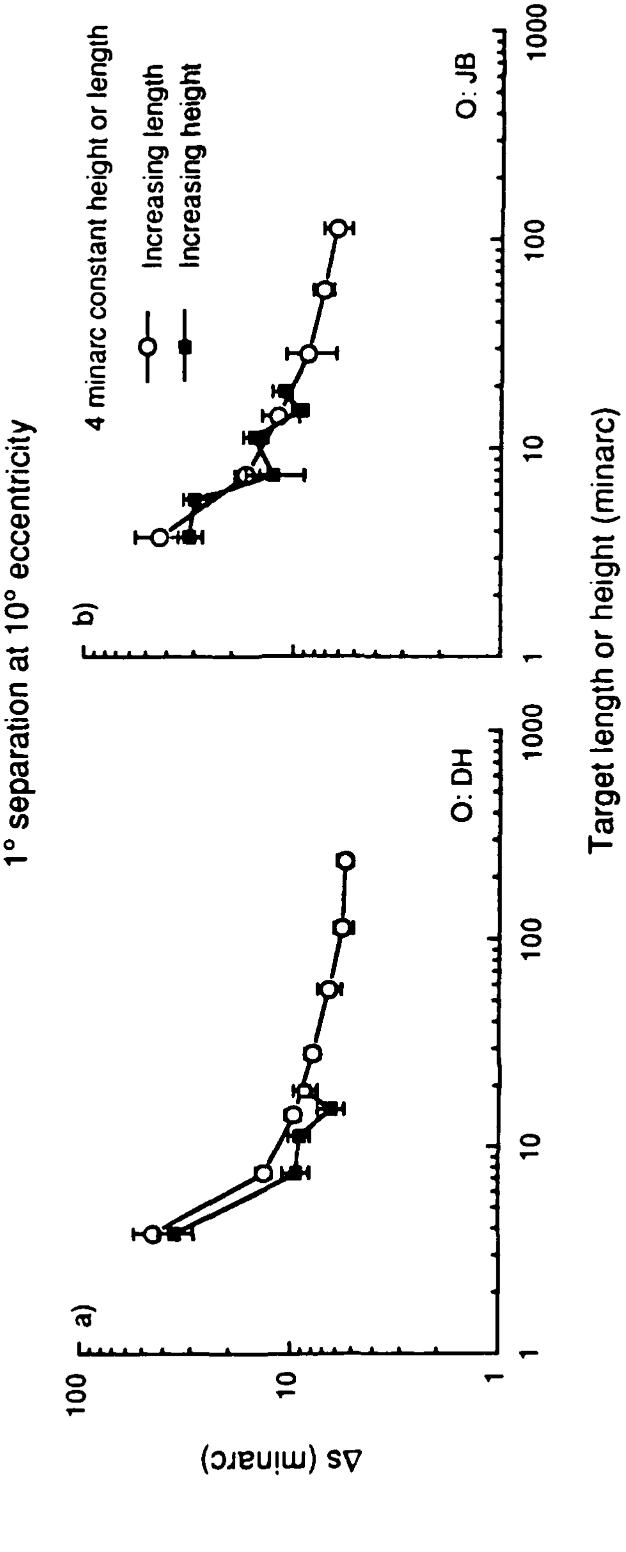
Fig. 11 Separation-discrimination thresholds plotted as a function of increasing target length for the flattest function obtained in each condition for observers DH and TRM. (The datum for the shortest length of 2 minarc has been excluded from the foveal 8 minarc function for observer TRM.) A shallow contrast-independent length effect was found for the smaller separation at each eccentricity. Little or no contrast-independent length effect was found for the larger separation at each eccentricity.

Fovea-centered stimuli

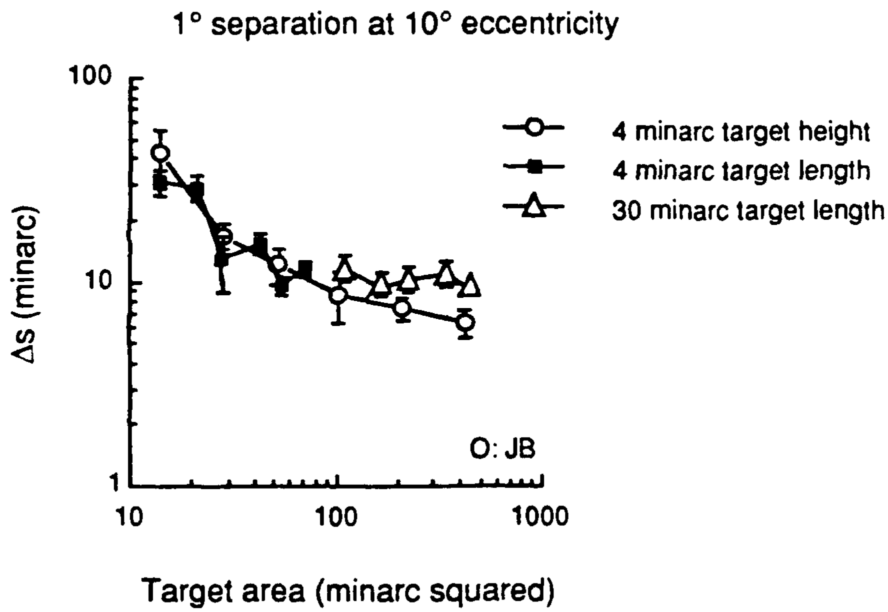


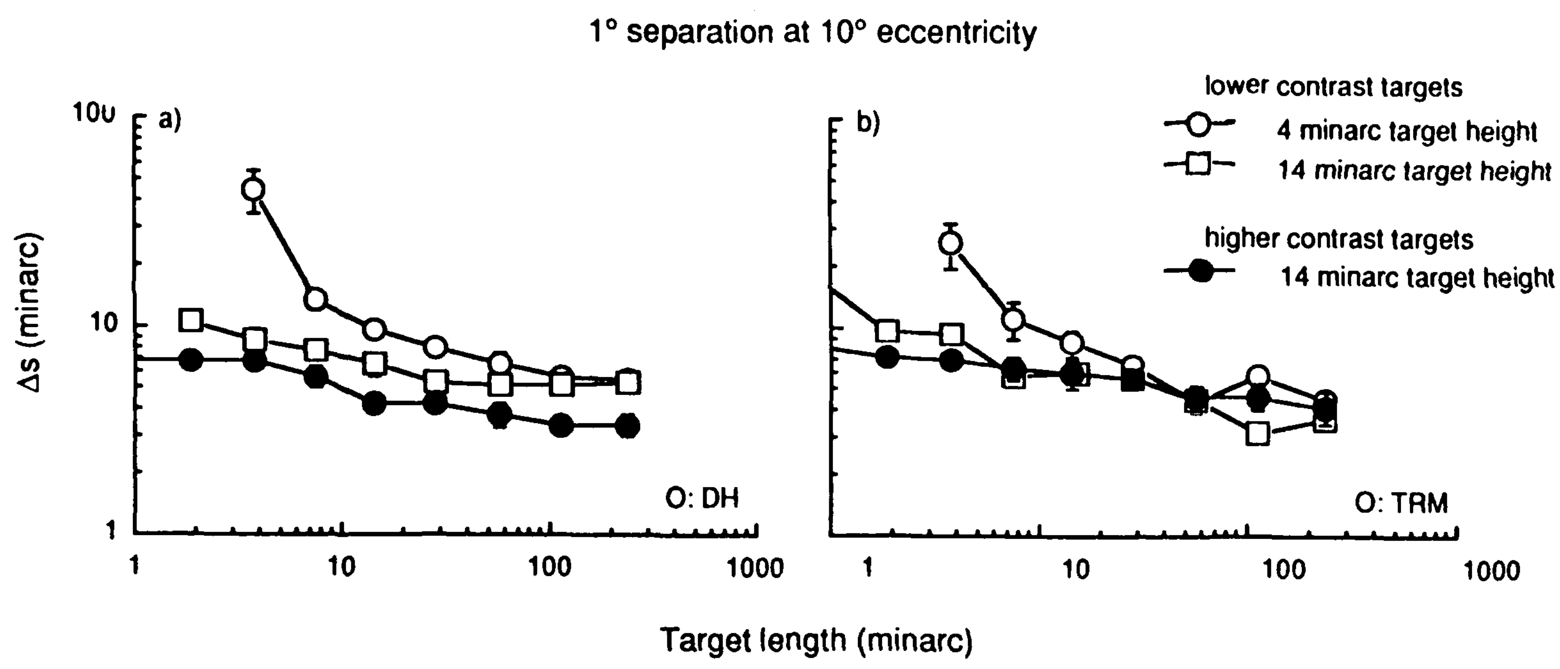
Peripheral stimuli

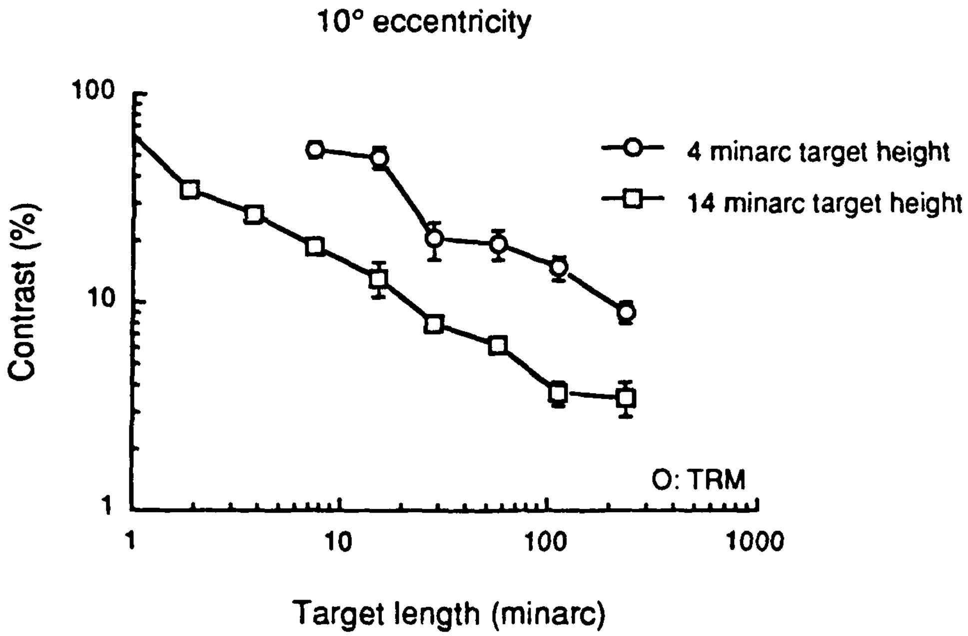


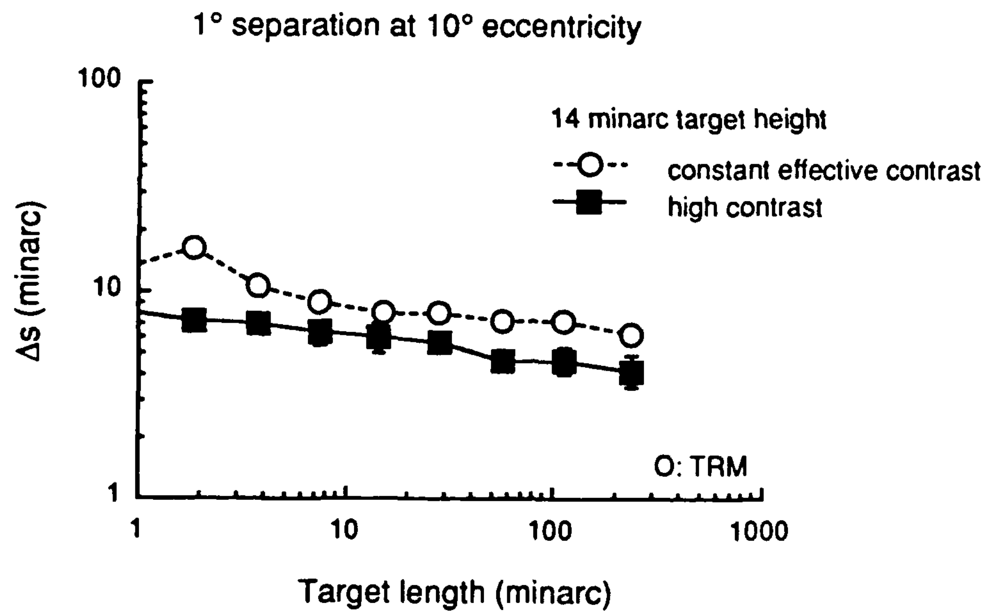


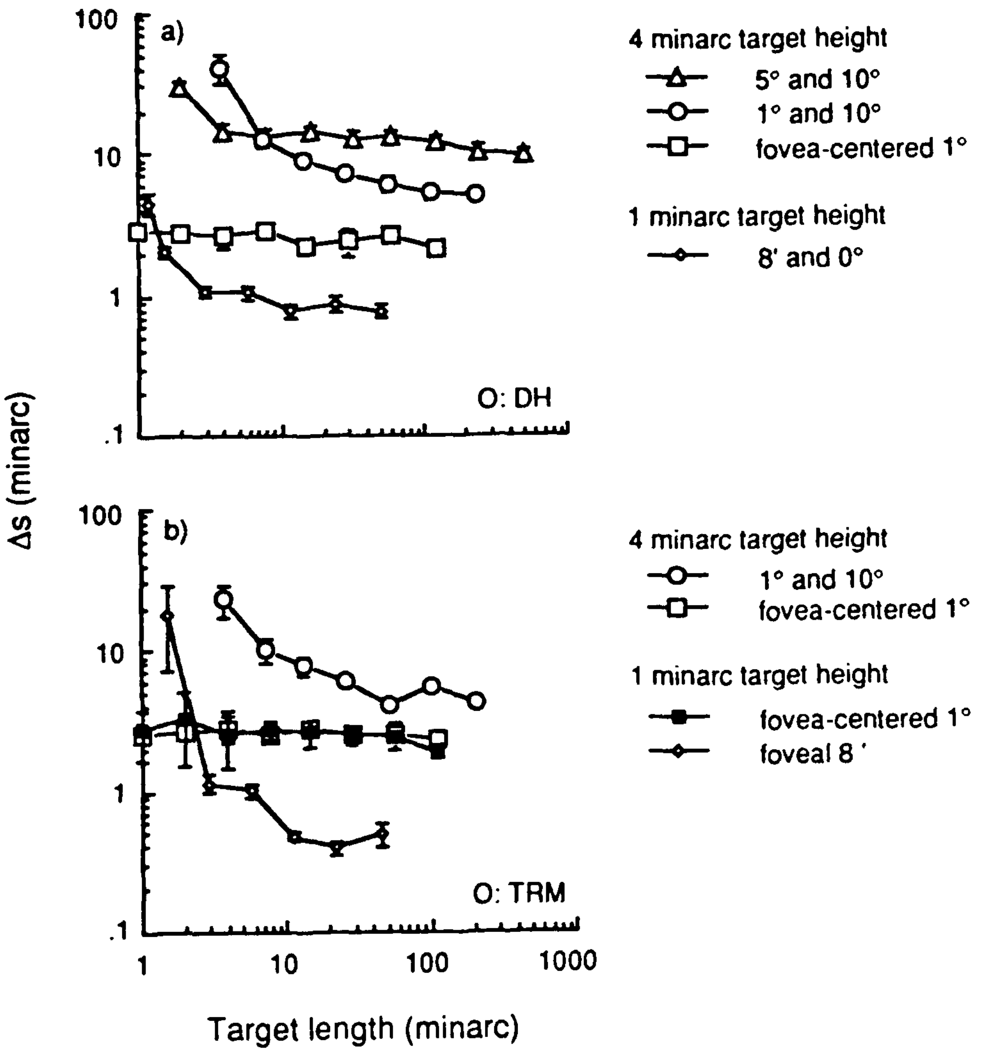
1° separation at 10° eccentricity
a)
b)
4 minarc constant height or length
Increasing length
Increasing height
O: DH
O: JB
Δs (minarc)
Target length or height (minarc)
100
10
1
1000


1° separation at 10° eccentricity
100
10
1
10
100
1000
Δs (minarc)
Target area (minarc squared)
4 minarc target height
4 minarc target length
30 minarc target length
O: JB


1° separation at 10° eccentricity
lower contrast targets
4 minarc target height
14 minarc target height
higher contrast targets
14 minarc target height
a)
b)
Δs (minarc)
100
10
1
1
10
100
1000
O: DH
O: TRM
Target length (minarc)

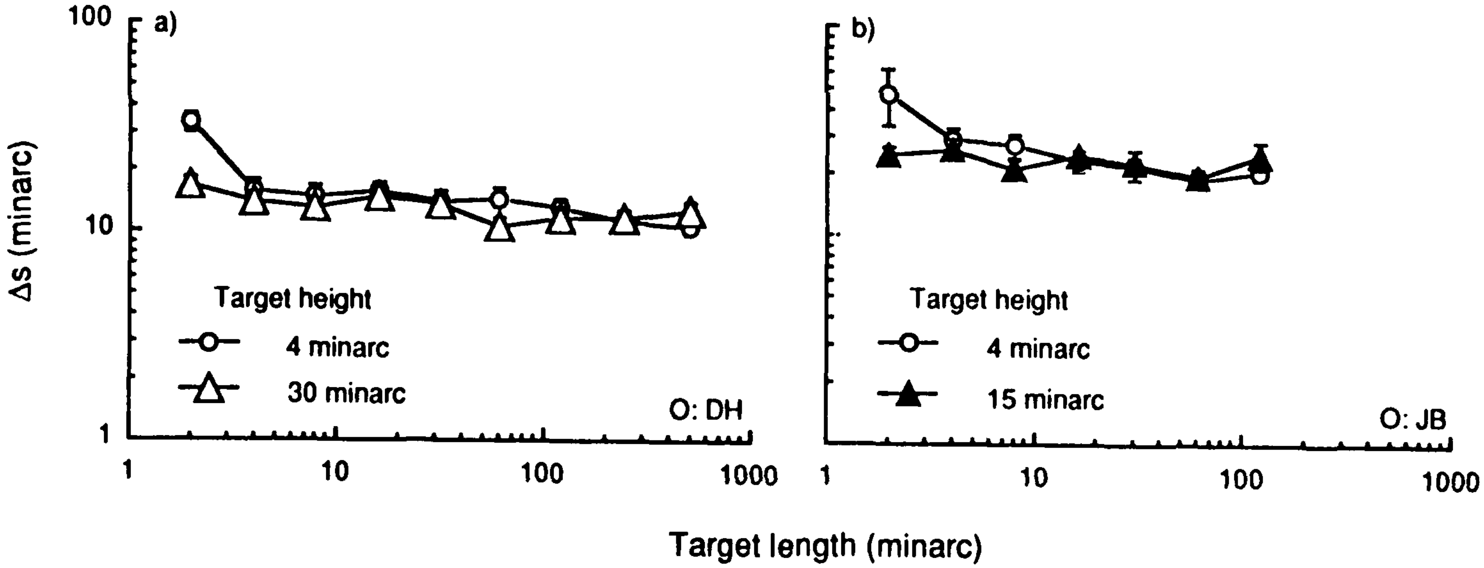

10° eccentricity
100
10
1
Contrast (%)
4 minarc target height
14 minarc target height
O: TRM
1
10
100
1000
Target length (minarc)

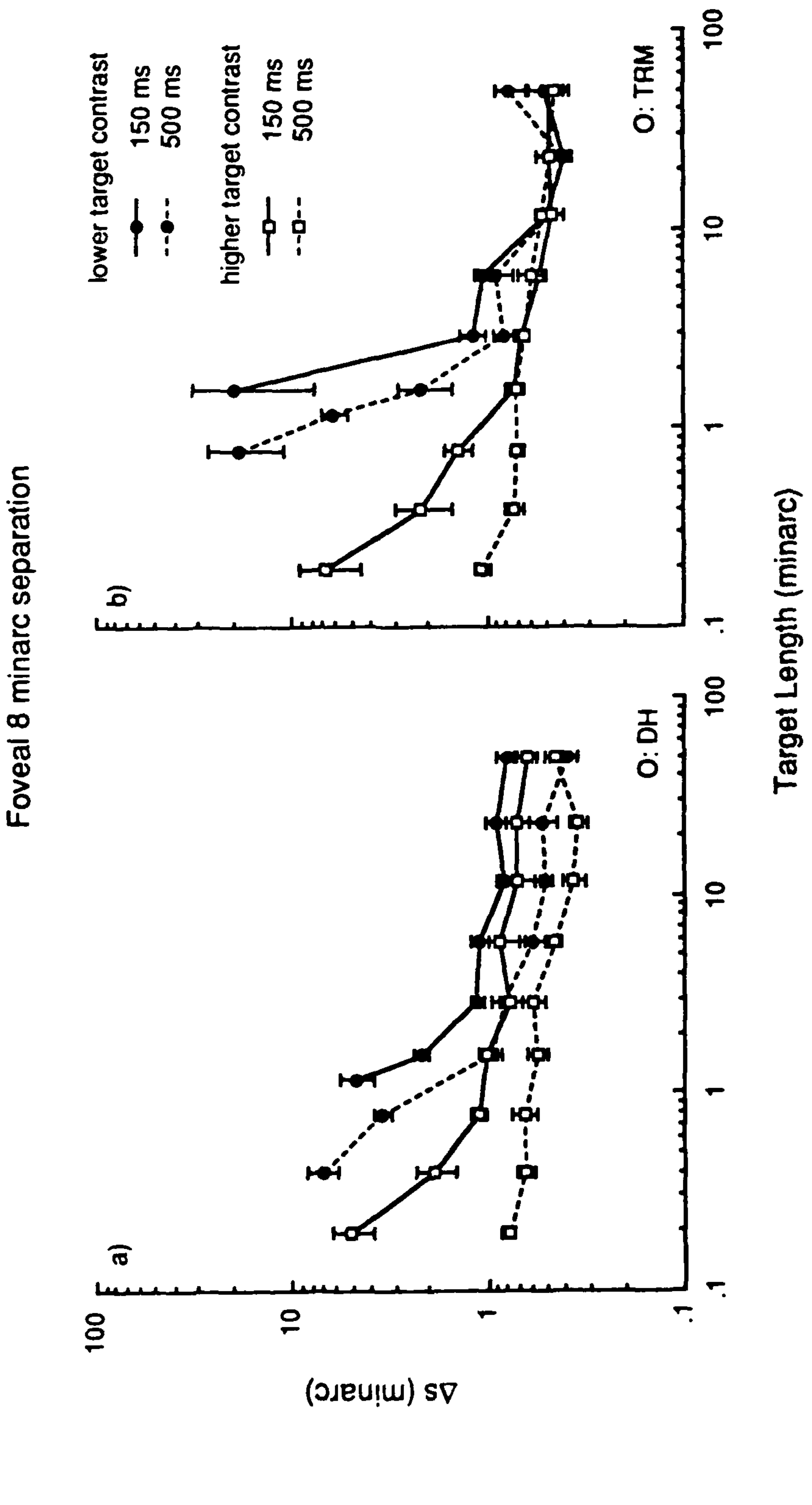

1° separation at 10° eccentricity
100
10
1
Δs (minarc)
14 minarc target height
constant effective contrast
high contrast
O: TRM
1
10
100
1000
Target length (minarc)



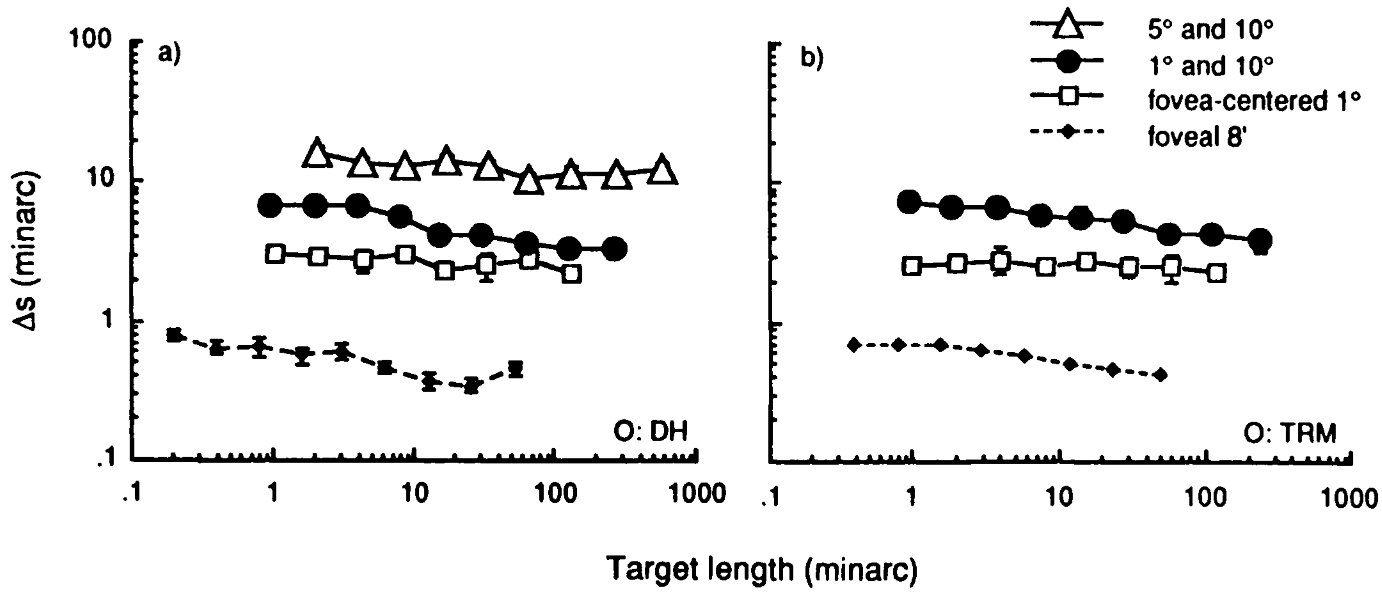
100
a)
10
1
.1
O: DH
4 minarc target height
5° and 10°
1° and 10°
fovea-centered 1°
1 minarc target height
8' and 0°
Δs (minarc)
100
b)
10
1
.1
O: TRM
1
10
100
1000
Target length (minarc)
4 minarc target height
1° and 10°
fovea-centered 1°
1 minarc target height
fovea-centered 1°
foveal 8 '

5° separation at 10° eccentricity




Foveal 8 minarc separation
a)
b)
Δs (minarc)
100
10
1
.1
Target Length (minarc)
O: DH
O: TRM
lower target contrast
150 ms
500 ms
higher target contrast
150 ms
500 ms

Contrast-independent length effect



Appendix C

SPATIAL-FILTER SELECTION IN LARGE-SCALE SPATIAL-INTERVAL DISCRIMINATION

SPATIAL-FILTER SELECTION IN LARGE-SCALE SPATIAL-INTERVAL DISCRIMINATION

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Abstract—Spatial-interval discrimination thresholds were measured for a pair of bars in the presence of other parallel bars placed far enough from the targets as to be outside the range of neural and optical blurring. Thresholds were elevated when the targets were embedded in an array of four parallel bars (two between and two flanking the targets), but not when there were only two parallels, whether the parallels were between the target bars or flanking them. The threshold elevation was larger with a 100-msec than with a 500-msec exposure duration. Attenuating the high spatial frequencies magnified the threshold elevation. The data indicate that the process responsible for spatial-interval discrimination automatically selects which spatial filters to use; it does not have to scan through all ranges of spatial filters.

Spatial scale   Local spatial filters   Spatial-interval discrimination   Exposure duration   Clutter

INTRODUCTION

Much research on spatial-interval discrimination has focused on attempts to explain the phenomenon in terms of the responses of individual local spatial filters, such as those postulated by Wilson and Bergen (1979) or Watson (1982). The idea has been that the spatial filters themselves carry the information about the size of the spatial-interval. In those models, large intervals are indicated by activity at low spatial frequencies, small intervals by activity at high spatial frequencies, and so forth (Wilson & Gelb, 1984; Klein & Levi, 1985). However, several studies have shown that manipulating the spatial frequency content of the stimulus has no effect on the interval judgment (Morgan & Ward, 1985; Toet, van Ekhout, Simons & Koenderink, 1987; Toet & Koenderink, 1988; Burbeck, 1987, 1988). For example, accuracy is as high for a pair of high-spatial-frequency targets as for a pair of low-spatial-frequency targets, even when the separation between the targets is so large that the high-spatial-frequency targets could not possibly be detected by the same spatial filter (Toet et al., 1987; Burbeck, 1987). Spatial-interval discrimination thresholds are also unaffected if one of the targets stimulates only high- and the other only low-spatial-frequency filters (Burbeck, 1988).

Collectively, these data suggest that the local spatial filters provide information about the positions of individual targets rather than about the separation between the targets. The critical problems thus are to discover the relationship between the spatial filters and separation or size judgments and, ultimately, to discover the nature of the process responsible for such judgments. The research reported here focuses on how information from local spatial filters is used in separation judgments.

Most of the experiments in the studies mentioned above used targets presented on uniform backgrounds. For such stimuli, any spatial filters whose responses vary significantly between trials could provide useful information; there is no need for the system to select among filters. Thus, these experiments leave open the question of whether the size processor is able to select which filters to use, or whether it responds automatically to any stimulation present.

Addressing similar questions, Morgan and Ward (1985) studied the effects of parallel flanking lines on spatial-interval discrimination for lines separated by a few (3, 6 or 12) min arc. They found no effects for flanking lines sufficiently far from the targets to eliminate optical or neural blur, and conclude that the spatial filters responsible must be extremely small (too small to detect both the targets and the flanking lines simultaneously). However, Morgan and Ward do not provide compelling evidence that larger filters are employed in the absence of flanking lines, nor do they provide a rule for changing between filter sizes. Thus, it is still not clear whether the size processor can choose the

best filter and, if it can, which filters it uses under which circumstances.

Watt (1987) has suggested that scale selection is automatic. Specifically, he suggests that although information is initially available at all scales, the visual system obtains its geometric information from the coarsest available filter. As time progresses, the larger spatial filter responses are switched off, leaving progressively smaller filters to convey geometric information. This model accounts for the effects of exposure duration on several spatial tasks, under the assumption that larger spatial filters provide poorer positional information. However, direct tests of that assumption find no such relationship (Toet et al., 1987; Burbeck, 1987, 1988).

The present study addresses the problem of scale-selection by examining jointly the effects of flanking lines and exposure duration. In this study a large separation is used to increase the range of spatial frequencies that carry pertinent information, thereby making it easier to determine whether the addition of parallel lines changes the range of spatial frequencies used in the discrimination task. The basic hypothesis being tested is as follows. We assume that larger spatial filters have higher signal-to-noise ratios than smaller spatial filters, on the basis of standard contrast sensitivity results. When the targets are presented on a uniform background, we hypothesize that the size processor uses the filter with the highest signal-to-noise ratio i.e. the largest spatial filter or lowest-spatial-frequency filter, that can detect one target without detecting the other. When there are lines flanking the targets, the large spatial filters respond to the flanking lines as well, and so yield unreliable information about the position of the target. In this case, a smaller filter, i.e. one tuned to a higher spatial frequency, will be used. Information from this filter is better in this case because it has a smaller receptive field size, and thus detects the targets without interference from the flanking lines.

We test this hypothesis by determining which spatial frequency ranges are carrying the relevant information with and without flanking lines. This determination is made by adding a diffusion screen to attenuate middle and high spatial frequencies in the stimulus and by varying the exposure duration, from 100 to 500 msec. Attenuating middle and high spatial frequencies by a diffusion screen shows directly the role those frequency ranges play in the determination of threshold. The exposure duration effect is more subtle. It has been shown previously that, for durations longer than about 100 msec, the effect of exposure duration on spatial-interval discrimination thresholds depends on which spatial-frequency range is carrying the relevant information (Burbeck, 1986). The effect is larger when the relevant spatial frequency range is high, regardless of the interval size. With the large intervals and bar targets used in the experiments reported here, exposure duration has at most a small effect when the targets are presented on a uniform field. If the addition of flanking lines causes the exposure duration effect to increase, it suggests that higher spatial frequencies are being used in the presence of the parallel lines than were used in their absence.

METHODS

Spatial-interval discrimination thresholds were measured using the method of constant stimuli. On each trial, a single pair of bars was presented and the observer was asked to report whether the separation between the bars was larger or smaller than the average separation seen on previous trials. The target separations (measured center to center) ranged from 2.77 to 3.07 deg. The average separation was 2.92 deg.

Our stimuli were displayed on a high-resolution monitor, which was controlled by a microcomputer. Details of this display are given elsewhere (Burbeck, 1986). The target and parallel bars each subtended 11.3 deg horizontally and 0.34 deg vertically. They were presented at 45% (Michelson) contrast on a 90 cd/m^2 background that measured 29 cm by 39.4 cm, or 10.6 deg vertically by 14.4 deg horizontally at the 155-cm viewing distance used. The position of the entire stimulus was varied randomly from trial to trial relative to the upper and lower edges of the display (within the range $\pm$ 19.3 min arc relative to the centered position) to prevent the edges of the display from providing useful position cues. The room was dark. Viewing was monocular, unless indicated otherwise. The exposure duration of the target and parallel bars was a parameter of the individual experiments.

The exact distance of each parallel from the nearest target was chosen randomly from trial to trial from the range 46–72 min arc (center-to-center). A range of distances to the parallels was used so that the distance between the parallels themselves (in particular, between the inner

parallels) could not be used to gain information about the target separation. The range that was used allows the bars to be clearly resolved. This range also places the parallels outside the range of neural crowding, as indicated by data on the effects of flanking lines on vernier acuity (Levi, Klein & Aitsebaomo, 1985) and on bisection (Yap, Levi & Klein, 1987). Both studies found that for retinal eccentricities less than about 2.5 deg, flanking lines have no effect when the distance between the target and flanking line exceeds 25 min arc. Because our target lines were seen at an average eccentricity of 1.46 deg (half of the 2.92 deg separation) and were always more than 25 min arc (edge to edge) from the nearest target, any effects of our parallels must be attributed to a mechanism other than the lateral interactions that affect vernier acuity and bisection thresholds.

The stimuli were presented with abrupt temporal onsets and terminations. Several exposure durations were used: 102, 255 and 510 msec, and a condition in which the stimulus was presented continuously until the observer responded (response-terminated condition).

Data were collected in sessions of 84, 154 or 294 trials (depending on the endurance of the observer); the first 14 trials in each session (which constituted the first block of stimuli) were for practice and were not included in the data analysis. At least 210 nonpractice trials were conducted for each condition and each observer. Threshold estimates from each session were determined at the 84% correct level by standard probit analysis techniques (Finney, 1971). For data collected from more than a single session, the geometric mean of individual threshold estimates was calculated with each individual threshold estimate weighed by its inverse variance. The between-session variability was incorporated into the standard error by multiplying the conventional standard error by the reduced χ^2 ($=\chi^2$/d.f.) for a reduced $\chi^2 > 1$. This method takes into account the goodness of fit of the geometric mean to the individual threshold estimates (Bevington, 1969).

A total of five observers was used. All had normal or corrected-to-normal vision.

RESULTS

Embedding the targets in an array of four parallel bars

In these experiments, spatial-interval discrimination thresholds were measured with the target bars embedded in an array of four parallel bars, as shown in Fig. 1a. Spatial-interval discrimination thresholds were also measured using just the target bars, with no extraneous parallels. These controls data were obtained under the same experimental conditions in sessions interleaved with the four-parallels data sessions.

Considering the stimuli in terms of their Fourier spectra, addition of the parallel bars

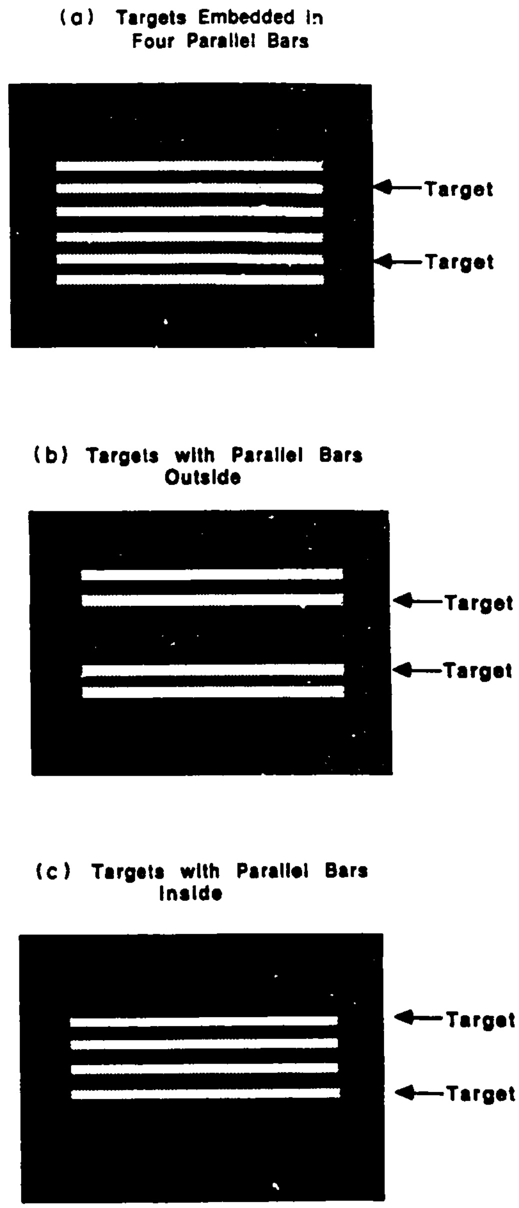

Fig. 1. Three of the stimulus configurations used. The distance between the targets was the independent variable in the experiment. The distance between each parallel and the nearest target was randomly changed from trial to trial and was determined separately for each parallel, so that, in general, the bars were not equally spaced.

adds energy at a broad range of spatial frequencies (because the bars are broad-band targets). The outside parallels add most energy at a frequency slightly lower than the separation frequency (the reciprocal of the target separation). The inside parallels add most energy at frequencies higher than the separation frequency. However, if we assume that the receptive field size of the local spatial filters decreases with increasing spatial frequency, then the smaller receptive fields of middle- and high-spatial-frequency filters give them an advantage not evident in the Fourier spectra: namely, if its receptive field size is sufficiently small, a local spatial filter could detect a target while being unaffected by the parallel bars. Thus, if the size processor can select the best filter, then it should select a middle- or high-spatial-frequency filter when the targets are embedded in four parallel bars, and it should select a lower-spatial-frequency filter when the targets are not flanked by other bars, under the assumption that a lower-spatial-frequency filter has a lower signal-to-noise ratio. The particular frequency range that would be best in each case would depend on the exact sensitivities and bandwidths of the local spatial filters as well as on the stimulus characteristics.

If the size processor does choose the best filter for the four-parallels condition, then at short exposure durations, thresholds may be elevated relative to the no-parallels condition (because thresholds based on the responses of high-spatial-frequency filters are elevated at short exposure durations). At longer exposure durations, however, the threshold with parallels should return approximately to the value obtained with no parallel bars. Previous research has shown that, for long exposure durations, spatial-interval discrimination thresholds are roughly equal whether based on low- or high-spatial-frequency information (Burbeck, 1986). However, the addition of parallel bars would be expected to add to the overall noise of the system. Thus, the key issue here is not whether the parallel bars elevate thresholds at all, but whether the effect of exposure duration is accentuated by the addition of the parallels. Most models based on the response of single filters would predict an overall change in sensitivity; thus any arguments based on such a result would have to be quantitative, and therefore critically model dependent. However, most models would not predict a change in the effect of exposure duration, and any such change would therefore be highly informative.

Data for two subjects and a range of exposure durations are shown in Fig. 2a and b. The data for the targets with no parallel bars show no effect of exposure duration, consistent with previous reports using large separations (Burbeck, 1986). However, when the targets are embedded in four parallel bars, the exposure duration effect becomes highly significant. Thresholds are substantially elevated at durations of 100 and 255 msec, and are elevated only slightly or not at all at the longest durations used. This is consistent with the hypothesis that the relevant spatial frequencies are shifted to a higher range by the addition of the parallel bars.

To test further the hypothesis that the visual system is using higher spatial frequencies to make the spatial-interval discrimination

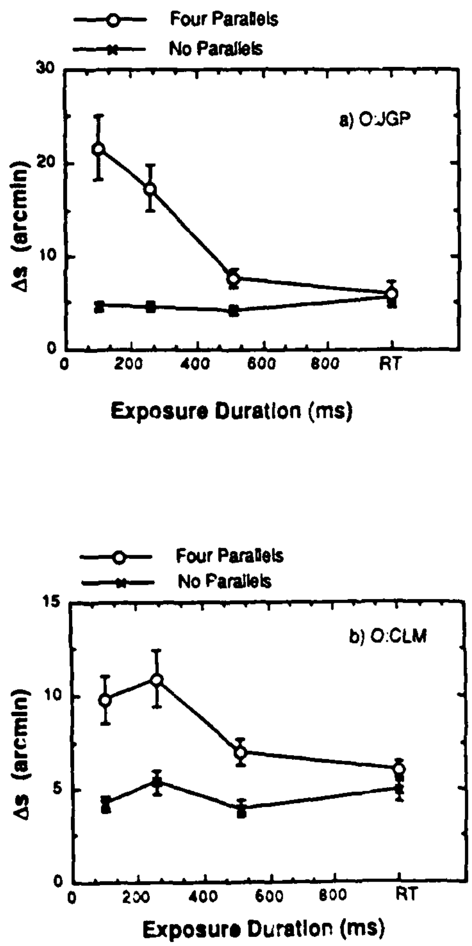

Fig. 2. Separation discrimination thresholds for a pair of bars embedded in an array of four parallel bars at four exposure durations: 102, 255 and 510 msec, and response-terminated. Also shown are data obtained without parallels. Data are shown for two observers

judgment when the targets are embedded in four parallel bars, we attenuated those higher spatial frequencies using a diffusion screen placed in front of the display monitor.

Spatial-interval discrimination with middle and high spatial frequencies attenuated

The spatial frequency characteristic of the diffusion screen was calibrated by measuring contrast sensitivities for horizontal sine-wave gratings with and without the screen in place. Contrast thresholds were measured using a standard yes/no staircase procedure. Eight pairs of contrast reversals from two interleaved staircases were averaged to yield an estimate of contrast threshold. The horizontal gratings subtended 12.4×9.1 deg and were presented for 100 msec. Other experimental conditions were the same as for the other experiments.

The ratios of the contrast thresholds obtained with and without the diffusion screen in place are plotted in Fig. 3. Contrast is rapidly attenuated with increasing spatial frequency. Thus if higher spatial frequencies are involved in the four-parallels case than in the no-parallels case, then the diffusion screen should have a more pronounced effect with four parallels present than with none.

Spatial-interval discrimination thresholds were measured with and without the diffusion screen in place. The ratios of these thresholds, which are a measure of the effect of the diffusion screen itself, are shown in Fig. 4. In the no-parallels case, the diffusion screen had a small significant effect. In the four-parallels case, there was a large significant effect whose magnitude depended on exposure duration. Although these data look like those shown previously (Fig. 2), in fact they tell quite a different story. Specifically they show that attenuating the high spatial frequencies had a larger effect with a 100-msec than with a 500-msec duration. This implies that high-spatial-frequency filters play an important role in determining the 100-msec threshold. This finding is not consistent with a coarse-to-fine analysis of the visual scene, as proposed by Watt (1987). This issue will be considered further in the discussion.

The data of Fig. 4 indicate that lower spatial frequencies are used when parallels are absent than when they are present. In short, when the low-spatial-frequency filters do not provide good information, higher-spatial-frequency filters are used.

Does the size processor always use high spatial frequencies in the presence of parallels or can it employ a strategy of using the best available information? To answer this question, we measured spatial-interval discrimination thresholds with just two parallel bars. These parallels either flanked the target pair, as shown in Fig. 1b, or lay between the targets, as shown in Fig. 1c. If the receptive fields used in these cases are the same as those used in the four parallels case, then the exposure duration effect should remain the same. On the other hand, if the relevant receptive fields are tuned to local spatial filters in the low- to medium-spatial-frequency range, then thresholds should not be substantially affected relative to the no-parallels case.

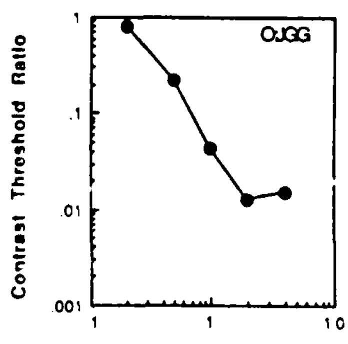

Fig. 3. Diffusion screen calibration. The contrast threshold ratios were calculated by dividing the contrast thresholds obtained without the diffusion screen by the contrast thresholds obtained with the diffusion screen in place.

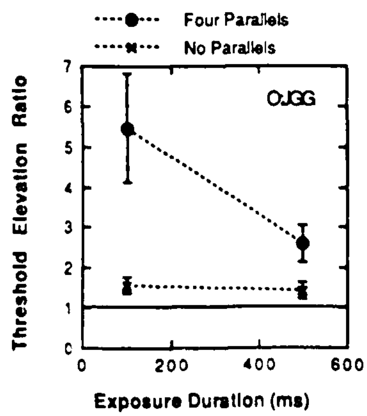

Fig. 4. Effects of the diffusion screen on separation discrimination thresholds measured with four parallel bars and with no parallel bars. The threshold elevation ratio was obtained by dividing the threshold obtained with the screen present by the threshold *for the same stimulus condition* obtained without the diffusion screen. Thus, this ratio indicates the effect of the diffusion screen only.

Spatial-interval discrimination with outside parallel bars

This experiment was identical to the initial experiment reported above except that the bars between the targets were removed, as shown in Fig. 1b. It is similar to an experiment performed by Morgan and Ward (1985) using small separations.

Two exposure durations were tested, 100 and 500 msec. Data for two observers are shown in Fig. 5. Also shown for comparison are data obtained with no parallels. (The inside-parallels condition, which is also shown in this figure, will be discussed below). At the short exposure duration, the outside parallels elevated thresholds significantly. However, informal observation suggested that the outside bars appeared to create a reference frame that affected the perceived depth of the targets. As that reference frame changed from trial to trial, the perceived depth of the target bars changed, and with that change in perceived depth seemed to come a change in perceived separation.

To test the validity of these observations, spatial-interval discrimination thresholds were remeasured with binocular viewing and dim room illumination to facilitate acquisition of depth information. If the outside parallels were affecting threshold by affecting perceived depth, then these changes would reduce or even eliminate the effect. Data were collected from two new observers for 100-msec duration, with monocular and binocular viewing in interleaved sessions. Data for the no-parallels and four-parallels conditions with both monocular and binocular viewing were also collected in interleaved sessions for comparison.

The data for the outside-parallels condition are shown in Fig. 6a and for the four-parallels condition, in Fig. 6b. Data are shown for two observers. The data obtained with monocular viewing replicate the effects reported above. One observer had a large effect, the other a small but significant one. [Large differences between observers in overall sensitivity are frequently obtained in separation discrimination experiments (Morgan & Regan, 1987; Yap, Levi & Klein, 1989; Levi & Westheimer, 1987)]. With binocular viewing, neither observer showed a significant effect of the outside parallels (Fig. 6a). For observer CAB, the ratio of the outside-parallels threshold to the no-parallels threshold was 1.4 ± 0.2 for monocular viewing and 1.0 ± 0.1 for binocular viewing. For observer MAC, the same ratio was 1.3 ± 0.2 for monocular and 1.1 ± 0.2 for binocular viewing. The absence of a significant effect of the outside parallels under binocular viewing conditions confirms the observation that the outside parallels affected the perceived depth of the target bars when viewing was monocular. Apart from this depth effect, the outside parallels had no effect on the separation discrimination threshold, suggesting that low-spatial-frequency filters can be used in the presence of parallels.

The change in viewing conditions did not have the same effect on thresholds for the four-parallels condition (Fig. 6b). For observer CAB, the ratio was 2.2 ± 0.5 for monocular viewing and 2.3 ± 0.5 for binocular viewing. For observer MAC, the monocular ratio was

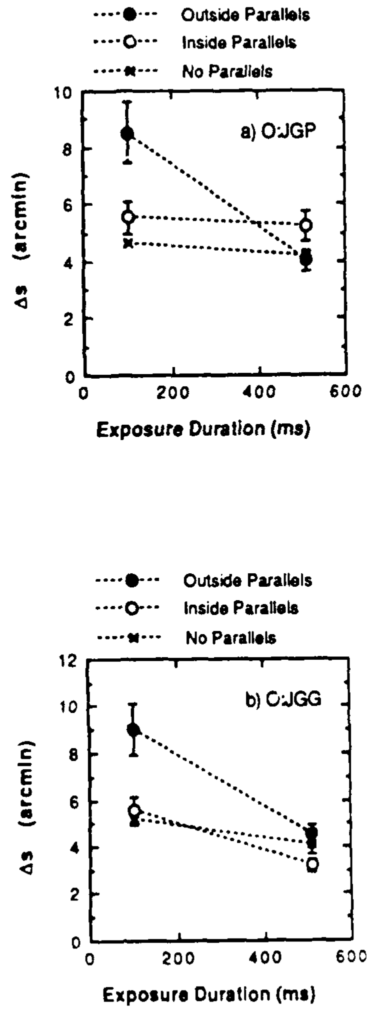

Fig. 5. Effects of two extra parallel bars on separation discrimination thresholds. Data are shown for two observers and two exposure durations. "Outside parallels" is the stimulus condition shown in Fig. 1b. "Inside parallels" is the stimulus condition shown in Fig. 1c. "No parallels" is the standard two-bar separation discrimination stimulus.

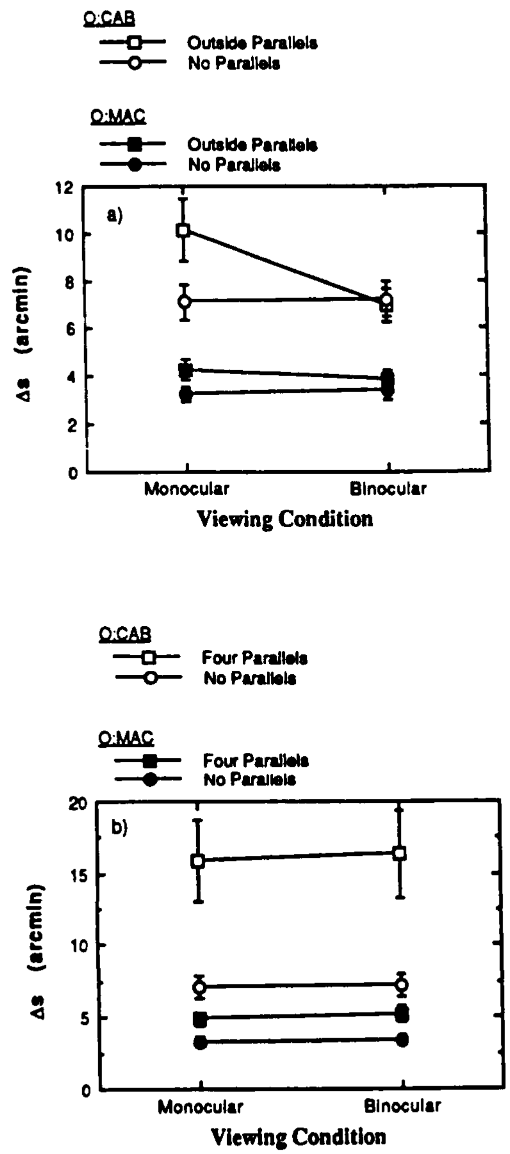

Fig. 6. Separation discrimination thresholds obtained under monocular and binocular viewing conditions. (a) Outside-parallels condition (squares) and no-parallels condition (circles). (b) Four-parallels condition (squares) and no-parallels condition (circles). Data are shown for two observers O:MAC, solid symbols. O:CAB, open symbols

1.5 ± 0.2 and the binocular ratio 1.5 ± 0.2. Thus, the effect of four parallels cannot readily be attributed to trial-to-trial changes in the perceived depth of the stimulus. The original hypothesis—that embedding the targets in four parallels changes the relevant range of spatial frequencies—is not contradicted.

Spatial-interval discrimination with parallel bars between the targets

Spatial-interval discrimination thresholds were measured in the presence of parallel bars lying between the target pair, as shown in Fig. 1c. All other experimental conditions were the same as in the previous experiments. Thresholds were measured for exposure durations of 100 and 500 msec.

Figure 5 shows data for two observers. For one observer, there was a small threshold elevation in the presence of the inside parallels that did not vary with exposure duration. For the other, there was a small significant decrease in threshold at the 500-msec exposure. Overall, the addition of bars between the targets had little effect, supporting our previous conclusion that low-spatial-frequency filters can be used in the presence of parallels. However, this result is not compatible with the idea that the separation itself is encoded in the response of a low-spatial-frequency filter, and we conclude that the separation is encoded at a higher level of processing than that at which local spatial filtering occurs. Given the large separation involved, that conclusion is not surprising.

We can readily explain why embedding the targets in four parallels has a substantial effect that varies with exposure duration, whereas presenting the targets with only two parallels does not. We begin by assuming that different local spatial filters are providing information about the target positions in each case. We further assume that within each filter size, the filters with the largest responses are used. These filters provide the highest signal-to-noise ratio, though not the highest sensitivity to local position. Previous research on large-separation discrimination indicates that contrast is a more important variable in this task than is local positional resolution. Increasing the contrast, up to about five times threshold, decreases the threshold significantly; enhancing the high-spatial-frequency content of targets does not (Burbeck, 1987). The argument proceeds as follows: When each target bar is crowded on only one side, as they are in the two-parallels conditions, they can be detected by filters of relatively low spatial frequency that are not centered on the targets. In this case, an odd-symmetric, low-spatial-frequency filter, such as an edge detector, could respond well to one of the targets and yet be unaffected by the outside parallels (although it would be strongly affected by an inside parallel). Similarly, another odd-symmetric filter could respond well to one of the targets but be unaffected by the parallels between the target pair (although it would be strongly affected by an outside parallel) When

the targets are embedded in four parallels, however, such filters would be stimulated by the parallels as well as by the targets and thus would be too noisy to be useful; smaller, even-symmetric filters, such as line detectors, would be most useful in this case.

As another means of testing whether low-spatial-frequency filters are used in the two-parallels conditions, we measured separately the effect of the diffusion screen on thresholds measured with inside parallels and with outside parallels. The results are shown in Fig. 7. (One of the observers whose data are shown in Fig. 5 was not available for retesting). Use of the diffusion screen does not have a significantly different effect in the two-parallels conditions from its effect in the no-parallels condition, although there is a suggestion of a slightly larger effect for the inside parallels than for the outside and no-parallels conditions. These data indicate that higher-spatial-frequency filters are involved in the four-parallels case than in the two-parallels cases. They also suggest that the same range of spatial filters may be responsible for the no-parallels and the two-parallels conditions.

DISCUSSION

The experiments reported here show that spatial-interval discrimination thresholds depend on the context within which the targets are placed. When the targets are embedded in an array of four parallel lines, the low spatial frequencies of the stimulus array no longer carry

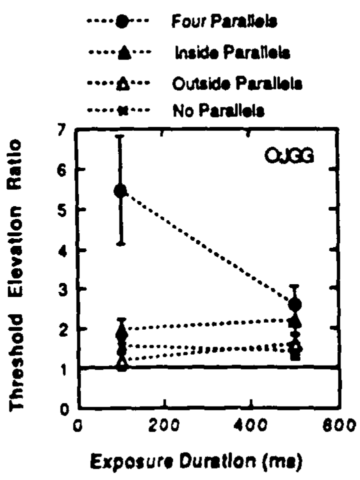

Fig 7 Effects of the diffusion screen on separation discrimination thresholds obtained with outside parallels (Fig. 1b) or inside parallels (Fig 1c) Also shown for comparison are the data from Fig. 5 obtained with four parallels and with no parallels.

the most accurate information about the positions of the individual targets. Under those conditions, spatial-interval discrimination thresholds are elevated, particularly at short exposure durations. This exposure duration effect together with the threshold elevation that results when the middle and high spatial frequencies are attenuated by a diffusion screen, indicates that. under these conditions, spatial-interval discrimination is being done on the basis of middle- or high-spatial-frequency information, which, according to current models, is obtained more locally than is low-spatial-frequency information. Thus, under cluttered conditions, units with smaller receptive fields appear to be used.

What are the rules governing this selection? Watt (1987) proposed that the frequency range of spatial filters in operation shrinks after stimulus presentation: initially the low-spatial-frequency filters provide information about the geometry of the stimulus and as time advances, the lower-spatial-frequency filters are switched out, leaving only the higher spatial-frequency filters to convey the information. (To account for data from a spatial resolution experiment, Watt theorizes that nongeometric information is always available at the finest scale, but such information is not important in our experiments). Can Watt's model account for our data? It appears to be compatible with our finding that in the four-parallels condition, accuracy improves over time. However, such improvement is also predicted by a theory in which high-spatial-frequency filters with long temporal integration times are always providing the information for this task [as postulated previously to account for the exposure duration effects seen in separation discrimination tasks involving small separations or large separations between high-spatial-frequency targets (Burbeck, 1986)]. The experiments conducted with the diffusion screen can discriminate between these two theories. If low-spatial-frequency filters are providing the information about the separation in the four-parallels case when the 100 msec duration is used, and the high-spatial-frequency filters are providing the information when 500 msec duration is used, then interposing the diffusion screen should have a smaller effect with a 100 msec than with a 500 msec duration. On the other hand, if high-spatial-frequency filters are providing the relevant information in both cases, then the diffusion screen should elevate thresholds as much, or more, with 100 msec

than with 500 msec duration. The data are conclusive. There is substantially greater threshold elevation with the 100 msec than with the 500 msec duration. This result is not consistent with a coarse-to-fine analysis, but is consistent with an *a priori* selection of the high-spatial-frequency filters as the preferred source of information for this task.

We propose that the rule for spatial scale selection is: Use the strongest signal that conveys the required information. If larger spatial filters have higher signal-to-noise ratios, then the rule is equivalent to: use the largest spatial filter that conveys the relevant information. In the case of separation discrimination with targets embedded in four flanking lines, the strongest relevant signal always comes from relatively small filters. Although the larger filters have the strongest signal initially, they do not provide the best information for this task because they are stimulated by the flanking lines as well as by the targets. When the targets are presented in an uncluttered field, the strongest relevant signal comes from larger spatial filters. If the observer has no prior knowledge of the stimulus or task, it may be that he will scan the filters from a coarse to a fine scale because the coarser filters often give the strongest response, especially initially. There is no data that we know of that is conclusive on this point.

There is some neurophysiological support for selection of the type we propose. In studies of the effects of attention, Desimone and colleages have found that if a monkey restricts his attention to one location within the receptive field of a neuron in area V4 (fourth visual area) or IT (inferotemporal cortex), "the response of the cell is determined primarily by the stimulus at the attended location, almost as if the receptive field 'shrinks' around the attended stimulus" (Wise & Desimone, 1988; Moran & Desimone, 1985). This spatial shrinkage could correspond to the transition from large, low-spatial-frequency filters to smaller, high-spatial-frequency filters that was evident in our study.

In sum, we have found that size judgments can be made on the basis of information from different spatial-frequency ranges under different experimental conditions. For widely separated target bars in an uncluttered field, lower spatial frequencies are used, but when the target bars appear in a cluttered field, higher spatial frequencies are sometimes used. These results add to the growing body of data indicating that information about the spatial interval is not carried directly in the responses of spatial filters, but that subsequent processing is required to extract the separation information.

In 1979, Westheimer eloquently argued that our sense of object position as "immediate, primary—not further reducible" should serve as a starting point for doing science in this area. Opposing this view were frequency-channel theorists who pooled all spatial properties in the responses of local spatial filters. Ten years later we appear to be returning to the idea that there is a specific process dedicated to determining the relative positions of objects or features. Spatial filters are still included in the discussion, but they are now components of a more complex process and not ends in themselves.

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Appendix D

SPATIOTEMPORAL LIMITATIONS IN BISECTION AND SEPARATION DISCRIMINATION

SPATIOTEMPORAL LIMITATIONS IN BISECTION AND SEPARATION DISCRIMINATION

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Exposure duration was found to have a different effect on bisection thresholds than on separation-discrimination thresholds. Bisection thresholds were higher than separation discrimination thresholds between 33 and 150 ms but equal to or lower than them at longer durations. Experiments in which stimulus contrast was manipulated showed that the effect of exposure duration on separation-discrimination and bisection thresholds could not be attributed primarily to temporal contrast integration. The data could be accounted for by a model in which bisection is done by encoding the two separations in bisection sequentially.

keywords: bisection, separation discrimination, spatiotemporal interaction, exposure duration, local spatial filters, spatial vision
running title: Spatiotemporal Limitations in Localization

INTRODUCTION

For more than 100 years, scientists have been interested in how the human visual system encodes inter-object distances. In the 1860's, Fechner and Volkmann (Fechner, 1860) investigated the problem in their quest to understand the domain of applicability of Weber's law , but little progress was made in understanding the underlying processes. In the 1970's, Westheimer rekindled interest in the subject through his research on hyperacuity (e.g., Westheimer, 1975) and his recognition that position is a basic, irreducible, visual property of objects (Westheimer, 1979).

A means of encoding information about the relative positions of objects was suggested by the discovery of size- or frequency-tuned mechanisms in human vision. Indeed, such mechanisms have proven to be helpful in accounting for some properties of separation-discrimination thresholds (Wilson and Gelb, 1984; Klein and Levi, 1985; Burbeck, 1986; Levi, Klein and Yap, 1988; Toet, Snippe and Koenderink, 1988; Yap, Levi and Klein, 1989). However, as recent experimental work shows (Morgan and Ward, 1985; Burbeck, 1987,1988; Toet and Koenderink, 1988; Burbeck and Yap, in press), these mechanisms are unable, by themselves, to account for the entire phenomenon.

More plausible than simple channel models is a two-stage model (Watt and Morgan, 1985; Burbeck and Yap, in press) in which the positions of the individual targets are encoded by localized spatial filters of various sizes and then estimates of inter-object separations are made at a subsequent stage of processing which, for brevity, we refer to as the *separation discriminator*.

Results of other experiments lend credence to the idea of a visual mechanism dedicated to encoding information about the relative locations of objects. In the research reported here, we investigate some of the temporal limitations of this theoretical separation discriminator.

The properties of the separation discriminator that have been uncovered so far suggest that it is quite a different type of mechanism than those postulated to account for contrast-detection thresholds. For example, whereas the size or spatial frequency of the target is a key parameter controlling contrast-detection thresholds (e.g., Robson, 1966), it is of little importance in separation-discrimination tasks. Separation-discrimination thresholds are largely independent of the size or spatial-frequency content of the individual targets, provided the signal strength is adequate (Burbeck, 1987, 1988; Toet and Koenderink, 1988). In particular, the separation discrimination threshold for a large separation between two high-spatial-frequency targets equals that obtained when the targets are of low spatial frequency only, or when one is of high and one of low spatial frequency, so that the two targets could not be detected by the same local spatial filter (Burbeck, 1988). These results suggest that although the targets may be detected individually by local spatial filters, the separation itself is encoded in a subsequent stage of processing. This conclusion is supported by other findings as well. For example, contrast-detection thresholds vary markedly with retinal eccentricity (Koenderink, Bouman, Bueno de Mesquita, and Slappendel, 1978; Rovamo, Virsu, and Nasanen, 1978), whereas, for a large range of separations, separation-discrimination

thresholds vary only slightly (Toet et al., 1988; Yap et al., 1989). Thus, contrast detection and separation discrimination exhibit some fundamentally different dependencies. This suggests that to understand the nature of the separation discriminator, we need to ask different questions than we do when studying contrast detection.

In the present study, we examine the temporal limitations of the separation discriminator. Specifically, we look at spatio-temporal interaction within the separation discriminator, asking the question: Are separation judgments performed simultaneously across the visual field [as was assumed when spatial filters were postulated to account for separation-discrimination thresholds], or does the separation discriminator operate sequentially on the various distances to be judged? The experiments reported here investigate the temporal limitations of the separation discriminator using standard *separation-discrimination* and bisection tasks. In the following, we treat the bisection task as a comparison between two simultaneously presented separations. Subsequent experiments described below test (and confirm) this model of bisection.

EXPOSURE-DURATION EFFECTS IN BISECTION AND SEPARATION DISCRIMINATION

To measure the temporal characteristics of the processes underlying separation discrimination and bisection, we measured thresholds for both tasks using two separations and a range of exposure durations.

Methods

We measured separation-discrimination and bisection thresholds, using horizontal line stimuli, for two reference separations: 11 arcmin (11′) and 2.8 degrees (2.8°). For the small separation, the target lines subtended 16 x 2′; for the large separation, they subtended 32 x 4′. The stimuli were presented at 45% contrast on a 90 cd/m^2 gray background (Conrac 2400, 19 in. diagonal, 60-Hz noninterlaced frame rate, 512 x 512 pixels), where contrast is defined to be $(L_{max}-L_{min})/2L_{mean}$. Viewing was monocular at distances of 10.3 m and 1.0 m for the small and large separation respectively, in an otherwise dark room.

The temporal and spatial configurations used in these experiments are shown schematically in Fig. 1. A trial began with a 500 ms presentation of a fixation line placed roughly in the middle of the display. This central fixation line subsequently served as one of the target lines. At the end of the fixation interval, the stimulus was displayed. In bisection, one line appeared above the center line and one appeared below, creating the standard three line bisection stimulus. The position of the middle line was changed from trial to trial. In separation discrimination, there were two temporal intervals. In the first interval, a line appeared above the fixation line, yielding the first separation to be judged; in the second interval, a line appeared below the fixation line, yielding the second separation, as illustrated in Fig. 1. The temporal intervals were separated by 500 ms, during which time the display was uniform at the mean luminance. Use of the central fixation line in both tasks ensured that the targets were presented in the same retinal locations.

Immediately following the stimulus presentation, a mask was presented for 500 ms. The mask consisted of three patches of sine-wave grating, one patch covering each target location. For the 11′ separation, the patches were 15 c/deg gratings subtending 16′ x 14′. For the 2.8° separation, they were 7.5 c/deg gratings subtending 32′ x 144′. The mask contrast was 90%.

To prevent the observer from using the position of the target relative to the mask as a cue, the mask was displaced from trial to trial by a random vertical distance. For the small separation, the range of mask displacements was ±8′ and for the large separation, ±80′. To prevent the observer from using the distance to the top and bottom display edges as a cue, the overall vertical position of the stimulus on the display was varied randomly between presentations by ±2′ to ±4′ for the small separation and ±20′ to ±40′ for the large separation.

Exposure durations for the test stimuli ranged from 33 ms to 500 ms. We could have fixed the test duration at 33 ms and varied the time until the mask appeared, instead of varying the test duration. The disadvantage of this strategy is that it implies that the stimulus strength is independent of the duration variable when in fact there are significant backward masking effects (see Breitmeyer, 1984 for a review). We preferred to determine what role stimulus strength played in the exposure duration effect by manipulating the contrast directly, as will be described subsequently.

In each trial, the two separations symmetrically bracketed the mean separation being tested, one larger and the other smaller than the mean. The separations differed by 1 to 7 units, the size

of the unit being varied as necessary with the separation and exposure duration to avoid both chance and perfect performance. The observer reported whether the upper or lower separation appeared larger. Right/wrong feedback was provided after every trial. By bracketing the separations around the mean, instead of presenting the mean as a reference on every trial, the observer was forced to compare the two separations to achieve optimal performance, rather than relying on a remembered value of the mean. Comparing only one separation to a remembered mean would elevate his thresholds by roughly a factor of 2.

The values used in calculating thresholds were the differences between the two separations presented, i.e., the difference between the upper and lower separations in bisection and the difference between the two sequentially-presented separations in separation discrimination. Each threshold point was based on at least 420 trials. Thresholds for individual sessions were calculated at the 84% correct level by standard probit analysis techniques (Finney, 1971). Threshold estimates from different sessions were combined by calculating the geometric means of the individual threshold estimates, weighted by their inverse variances. The error bars include both within- and between-session variability (Klein and Levi, 1987).

Three observers were used in these experiments. All had normal or correctable-to-normal vision. All were naive as to the purposes of the experiment.

Results

Figure 2 shows results of these experiments for all three observers and both separations. As expected, thresholds for the 2.8° separation were substantially higher than those for the 11′ separation. For both separations, thresholds decreased markedly with increasing stimulus duration, particularly between 33 and about 150 ms. At longer durations, thresholds continued to decrease for the small separation, but for the large separation, the separation-discrimination thresholds appeared to flatten. This is consistent with the results of a previous separation-discrimination study in which the effect of exposure duration was studied in the 100 to 500 ms range (Burbeck, 1986).

The slope of the upper portion of the curves in Fig. 2 is similar for the two separations, averaging about -0.7 to -0.8 for the three observers. Thus, there was substantial integration of information about separation between 33 ms and 150 ms for both separations. There was not, however, the simple linear relationship between the two variables that would indicate perfect temporal integration.

The data in Fig. 2 exhibit another important, although more subtle, property. Exposure duration had a different effect on bisection thresholds than it had on separation discrimination thresholds. At short durations, separation-discrimination thresholds were consistently lower than bisection thresholds, whereas at long durations, bisection thresholds were lower than separation-discrimination thresholds. This pattern held for both the large and the small separation (except for observer JM for long durations at the small separation).

In classical terms, one would say that the temporal

characteristics depend on the spatial properties of the stimulus, that is, on whether there are two lines or three. In other words, there is spatio-temporal interaction. A more detailed analysis indicates a possible source of this interaction.

ANALYSIS OF THE EXPOSURE-DURATION EFFECTS: LOCAL SPATIAL FILTER MODEL

Our strategy for investigating the properties of the separation discriminator was to try first to account for the data in terms of the local spatial filters that constituted the first stage of spatial processing in our model. If the filters could not account for the data, then new attributes would be ascribed to the separation discriminator. These new attributes must, in turn, be checked by additional experimentation. In a previous study using this approach, Burbeck (1986) was able to account for the effects of exposure duration on separation-discrimination thresholds in terms of the properties of the local spatial filters, without having to ascribe any temporal integration to the separation discriminator. However, that study included only exposure durations greater than 100 ms. The data obtained with shorter durations exhibited quite different properties: the effects were larger and they were, at least to a first approximation, independent of target separation.

To keep our analysis as general as possible, we adopted a generic local-spatial-filter model with a range of filter sizes at each eccentricity, and with smaller spatial filters having longer integration times than larger filters. We have found previously

(Burbeck and Yap, 1990) that separation discrimination thresholds are mediated by higher spatial frequency filters when the targets are embedded in an array of like objects than when they are not. Thus, exposure duration has a greater effect when the targets are so embedded than when they are not. Correspondingly, it may be that exposure duration has a greater effect on bisection than on separation discrimination because the center line in bisection is embedded in an array of like objects, whereas neither of the separation discrimination targets are.

Although this explanation of the interaction between the exposure-duration effect and the task (bisection or separation discrimination) may work for small separations, it loses plausibility when the larger separation is considered. With the larger separation, the outer lines are not close enough to the center line to cause the type of crowding described above. Therefore, if the effect is caused by such crowding when the separation is small, then there must be different causes for the effects at large and small separations.

To test whether the phenomenon that is occurring with the small separation is the same as that occurring with the large separation, we made a direct comparison between the data in the four conditions (bisection and separation discrimination at 11′ and at 2.8°). To facilitate this comparison, we normalized the data for each observer individually by dividing each curve by the threshold value obtained for that condition at the shortest duration (33 ms).

The normalized data are shown in Fig. 3. Small differences in slope were revealed by the difference in the normalized

thresholds at the longer durations: for two of the three observers (JB and PA), the bisection data and the separation-discrimination data formed two distinct clusters. For both observers, the normalized separation-discrimination thresholds were higher than the normalized bisection thresholds, regardless of separation. Within each task, the size of the reference separation interacted with the exposure-duration effect, as reported previously, but this interaction was a secondary effect. For observer JM, the data did not cluster by either separation or task. Overall, the data grouped according to task, i.e., bisection or separation discrimination, rather than separation. This suggests that a local-spatial-filter model is not the correct explanation for the small separation data.

ANALYSIS OF EXPOSURE-DURATION DATA: SEQUENTIAL PROCESSING MODEL

Because we could not account for the difference between the bisection and separation-discrimination data in terms of local spatial filters, we looked to the separation discriminator itself. A simple description of the difference between the separation-discrimination and bisection tasks is that separation discrimination involves sequential presentation of the two separations to be compared, whereas bisection involves simultaneous presentation of those two separations. If the separation discriminator can judge two separations simultaneously, then bisection thresholds should always be less than or equal to separation-discrimination thresholds. Lower thresholds might be

expected for bisection than for separation discrimination because separation discrimination requires that the observer remember the first separation for comparison with the second, whereas in bisection the comparison is immediate.

The fact that bisection thresholds were higher than separation-discrimination thresholds at short durations suggests that the separation discriminator could not process the two separations in the bisection task simultaneously. If, instead, the separation discriminator were acquiring information about the two separations sequentially in both tasks, then, in the bisection task, it would have less time for each judgment. The simplest model of this temporal limitation is that the observer has effectively half as much time to process each separation in the bisection task as he has in the separation-discrimination task.[1]

To test this model, we shifted the bisection data to the left by a factor of two, so that the bisection threshold for a t ms exposure duration was plotted at t/2 ms. The results of this transformation are shown in Fig. 4. Bisection thresholds are now generally less than or equal to the separation-discrimination thresholds, as they should be if processing were identical except for the delay between intervals in separation discrimination.

We assumed that the residual difference was caused by the loss of information between the intervals in the separation discrimination task. Because the inter-stimulus interval was constant across exposure durations, the information lost during

[1] At the shortest durations, the observer may spend all of his time attending to one of the two separations in the bisection task, but this would not generally be an effective strategy.

that interval should also be constant. We estimated the effect of this loss by taking the difference between the bisection and separation-discrimination thresholds at the longest exposure durations, where any effects attributable to temporal limitations were minimized.[2] Specifically, we took the difference between the bisection threshold at 500 ms (plotted at 250 ms in Fig. 4) and the nearest equivalent separation-discrimination threshold, which is at 300 ms, and subtracted this difference from the separation-discrimination thresholds at all durations. We performed this procedure independently for each observer and each separation.

The results of this transformation are shown in Fig. 5. The thresholds for separation discrimination and bisection now agree closely (except for the large-separation data of Observer JM). Thus the data are consistent with the sequential-processing model: the two separations are evaluated sequentially in both bisection and separation discrimination, but in separation discrimination there is a time lag in which information is lost.

SITE OF THE EXPOSURE-DURATION EFFECT

We have found that separation-discrimination and bisection thresholds decreased markedly with increasing exposure duration between 33 and 150 ms, regardless of the separation. The

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[2] Subtracting the average difference would have assumed *a priori* that the information loss was constant and would have tended to hide any deviations from constancy in the data. Use of the difference at the longest duration tests that assumption and reveals the extent to which the assumption is valid.

difference between the bisection and separation-discrimination data indicates that at least part of this improvement is attributable to the temporal properties of the separation discriminator itself. However, the data do not imply that all (or even most) of the improvement occurs within the separation discriminator. It may be that the exposure-duration effect occurs primarily within the local spatial filters, in the form of temporal contrast integration. If so, then the form of the functions graphed in Fig. 2 is determined primarily by the temporal properties of the local spatial filters and only secondarily by the separation discriminator.

This possibility contradicts the sequential-processing model of bisection, which implies that the separation discriminator is the primary source of the exposure-duration effect. The reasoning is as follows.

Our model of separation discrimination has two stages, local spatial filters and the separation discriminator. Local spatial filters operate on the stimulus in parallel. The effect of exposure duration on the filter outputs will, therefore, be the same for bisection and for separation discrimination. (We have already shown that the set of filters that detect the targets in the two tasks do not differ significantly in their temporal properties.) In the sequential-processing model, the two separations in bisection are processed sequentially. Since processing by the local spatial filters is done in parallel, shifting the bisection data by a factor of 2 along the exposure duration axis implicitly assumes that the processing of the individual targets by the local spatial filters contributes only

secondarily to the form of the functions in Fig. 2, under our high contrast conditions.

We assumed that within the local spatial filters, exposure-duration effects are caused by temporal contrast integration, an assumption supported in this context by other studies (Burbeck, 1986; Burbeck and Yap, in press). We then tested the implication that most of the temporal limitation evident in the data occurs in the separation discriminator by looking at the effect of target contrast on performance of our tasks. We investigated the role of temporal contrast integration in the exposure-duration effect of Fig. 2 by holding the effective contrast of the stimulus constant across exposure durations. We did this by making the stimulus contrast equal to a fixed multiple of the observer's detection threshold at each exposure duration.

Methods

We began by measuring contrast thresholds for the stimuli used in the original paradigm. The center fixation line was presented at 45% contrast for 500 + t ms, where t is the target exposure duration (see Fig. 1). The target line was flashed for t ms, 500 ms after the onset of the fixation line. In these contrast-detection experiments, the target line could appear above or below the fixation line. The observer's task was to report in which hemifield the target was presented. We varied the contrast of the target, using the method of constant stimuli, to determine the observer's contrast-detection threshold. A 90% contrast sine-wave grating mask immediately followed termination of the target, as in the original experiment. All other conditions, including

the separations and target sizes, were the same as in the original experiments. Thresholds were calculated, on the basis of 420 trials.

After measuring contrast-detection thresholds for the full range of exposure durations at both separations, we measured separation-discrimination and bisection thresholds using stimulus contrasts that were constant multiples of these detection thresholds. For the 11′ separation, we used two times the detection threshold, which was the largest integral multiple that we could use and still keep all target contrasts below 50%. (We can achieve no more than 50% contrast for a white line, because the background on our display is set to half the maximum luminance.) For the 2.8° separation, we used three times the detection threshold. We could use a larger value for 2.8° than for 11′ because the detection thresholds were lower for the larger targets of the 2.8° separation.

These separation-discrimination and bisection experiments were identical to those of the initial experiments, except that the contrasts of the targets were held at constant multiples of the detection thresholds. One observer was used. He did not participate in the original experiment.

Results

The contrast-detection thresholds, Fig. 6, show the expected decline with increasing exposure duration. The separation-discrimination and bisection thresholds obtained with these constant-effective-contrast stimuli are shown in Fig. 7(a). Even with effective contrast held constant, there is a clear decline in

threshold with increasing exposure duration. Also, the separation discrimination thresholds are significantly lower than the bisection thresholds for durations up to 150 ms ($F = 13.0$, $p<0.002$ for a separation of 11′ and $F = 6.6$, $p<0.02$ for a separation of 2.8°), as we found using higher contrast stimuli with other observers. At longer durations, the thresholds became equal.

Figure 7(b) shows the data after being transformed according to the sequential-processing model. (The bisection thresholds were shifted to the left by a factor of 2. There was no residual difference at 250 ms.) The results of this transformation are noisier than those in Fig. 5, but statistical analysis shows that the difference between the transformed-bisection and separation-discrimination curves (excluding the points at 33 ms and 500 ms which have no counterparts because of the translation) is only weakly significant for a separation of 11′($F = 3.8$, $0.1 > p > .05$) and not significant at all for a separation of 2.8° ($F = 0.62$, $p > .45$).

Because the difference between the separation discrimination and bisection thresholds was small under these conditions, we repeated the experiment with a higher constant contrast, using the large separation. (We could not raise the contrast of the smaller separation stimuli and maintain a constant multiple of the detection threshold.) Fig. 7c shows the results obtained with the contrast set to four times the observer's contrast detection threshold. As expected, the data are less noisy. The pattern of results is similar to that seeen with a lower contrast: bisection thresholds are higher than separation discrimination thresholds at short durations and equal at long durations. Thus, the effect is

reproducible.

The effect of exposure duration in these data is less than in the original experiments. This difference may reflect the contribution of temporal contrast integration in the original data, but intersubject variation may also be a factor. To assess directly the contribution of temporal contrast integration, we collected some additional data on this observer using high contrast targets. Rather than repeating the entire experiment, we restricted our comparisons to the shortest and longest durations. At 33 ms, the test contrasts used in the constant effect contrast experiments were quite high (because the detection thresholds were quite high). For the 11′ separation, contrast was 41% and for the 2.8° separation, it was 37%. Because these values were close to the 45% contrast used originally, thresholds were not remeasured using a higher contrast. At 500 ms, however, the detection thresholds were much lower, so the contrasts used in the constant effective contrast experiments were much lower For this condition, we remeasured separation discrimination and bisection thresholds using high contrast (45%) targets. As expected, thresholds were lowered.

Comparison between these (500 ms, 45%) thresholds and those obtained at 33 ms shows the overall effect of increasing exposure duration, including the effects of temporal contrast integration. Comparison of the constant effect contrast data and the high contrast data for the 500 ms condition shows how much of the overall effect is attributable to temporal contrast integration.

In all cases, temporal contrast integration contributed less than half of the overall effect. Temporal contrast integration had

more of an effect at the small separation than at the large, consistent with previous findings. Data will be given for the smallest and largest contrast effects. The smallest contrast effect was for separation discrimination with a 2.8° separation. The overall effect of contrast and exposure duration was to decrease threshold to 55% of the 33 ms value. Of this decrease, 94% was attributable to exposure duration per se, and 6% to temporal contrast integration. The largest contrast effect was for bisection at 11'. The overall effect was to decrease threshold to 19% of the 33 ms value. Of this decrease, 53% was attributable to exposure duration per se, and 47% to temporal contrast integration. These values represent upper bounds on the effect of temporal contrast integration: The 33ms thresholds would have been somewhat lower had 45% contrast been used, resulting in a smaller effect of temporal contrast integration. We conclude that the primary effect of exposure duration is not attributable to temporal contrast integration. This is consistent with the sequential-processing model of bisection.

DEFINING THE BISECTION THRESHOLD

In the above analyses, we assumed that in bisection, the observer's response is based on his judgment of which of the two separations (created by the three lines) is larger. On the basis of that model, we defined the bisection threshold in terms of the difference between the two separations. To test the validity of this definition, we compared thresholds for two bisection tasks and separation discrimination. We used a long duration and no

masking stimulus, so that the temporal limitations evident in the previous experiments would not affect the results.

Methods

We measured separation-discrimination and bisection thresholds, using horizontal line stimuli, for a reference separation of 2.8 °. The separation discrimination task that we used had one temporal interval, with a remembered mean serving as the reference separation. The reference separation was inferrred by the observer during practice trials, and maintained during the experiments by providing right/wrong auditory feedback after each trial. A previous study has shown that thresholds obtained with a remembered mean are as good or nearly as good (depending on the subject) as thresholds obtained with a two-alternative paradigm in which the referent is presented (Burbeck and Swift, 1988). This paradigm has the advantage that the temporal envelope is the same for bisection and separation discrimination. In bisection, the position of one line was changed from trial to trial. Either the middle line was moved (this task will be called bisection_m) or the top line was moved (bisection_t). Bisection_m was the task used in the studies reported above. Bisection_t was included to check the generality of the results. Right/wrong auditory feedback was provided after each trial.

The target lines subtended 32 x 4'. Viewing was monocular at a distance of 2.1 m. The stimuli were presented at 45% contrast. The exposure duration was 500 ms to allow processing to be complete for both tasks. Subjects fixated the center of the display screen; no fixation targets were used. The target lines

were displaced vertically by a random distance in the range ±15′ to prevent the top and bottom edges of the screen from being used as a cue to position. All other experimental details were the same as in the previous experiments.

Because the issue being addressed in these experiments is whether our definition of the bisection threshold is valid, we report the results in terms of an assumption-free description of the stimulus. Specifically, we report the thresholds in terms of the distance that one or more target lines was displaced relative to the others. The effect on each task of a displacement of one line by Δs is shown in Fig. 8. Our "comparison-between-separations" definition of the bisection threshold predicts that at threshold, the difference between the separations being compared in the three tasks will be equal. In terms of the distance that one line is displaced, this means that the threshold displacement for separation discrimination should equal that for $bisection_t$ and should be twice that for $bisection_m$, if our model of bisection is correct.

Results

The experimental results are shown in Fig. 9. The separation discrimination threshold is not significantly different from the $bisection_t$ threshold and is twice the $bisection_m$ threshold. These findings are exactly those predicted by the comparison-between separations model of bisection. This factor of two between the separation discrimination and $bisection_m$ thresholds was reported nearly 100 years ago by Fischer (see Table 1). He had his subjects either halve the horizontal or vertical arms of a cross

or set each arm of a cross equal to a given arm. Thresholds for the two tasks differed by a factor of two, when measured in terms of the displacement of the intersection.

The similarity of the separation discrimination and bisection$_t$ thresholds confirms the previous finding (Burbeck and Swift, 1988) that the remembered referent is represented internally with a level of variance that is similar to that associated with perception of a physically presented separation.

Discussion

Bisection was originally investigated as a task involving the direct comparison of a variable separation to a standard separation (Volkmann, 1857 as cited by Fechner, 1860). However, the literature has more recently been dominated by the view that bisection involves a comparison to the inferred center. This definition of the bisection threshold assumes that the observer mentally bisects the distance between the two outer lines and compares the position of the middle line to this mental representation of the center point. Such a model would be necessary if bisection thresholds were significantly lower than could be accounted for in terms of separation discrimination thresholds, but bisection thresholds are not inexplicably low. Thresholds for locating the center of a circle are exceptionally low, but this phenomenon does not extend to locating the center between two dots (Hirsch and Groll, 1986). Furthermore, the bisection threshold can be predicted directly and simply from the separation discrimination threshold. According to the comparison-to-inferred-center model of bisection, this relationship is coincidental. Parsimony clearly favors the comparison-between-

separations definition of bisection, which we have used in the results reported above.

The choice of bisection definition can profoundly affect the conclusions drawn. Specifically, use of the comparison-to-inferred-center definition creates a factor of two difference between the separation discrimination and bisection$_m$ thresholds that must be accounted for. Table 1 lists some studies of bisection and the definition that they used.

SITE OF THE MASKING EFFECT

In the experiments on the temporal limitations of bisection and separation discrimination reported above, we presented a masking stimulus at the termination of each test stimulus to interrupt processing. The sequential-processing model of bisection implicitly assumes that the mask interrupted processing within the separation discriminator itself. This assumption is supported by the results of the constant-effective-contrast experiments. If the mask had not interrupted processing within the separation discriminator, then the equal effective contrast stimuli would have resulted in equal separation-discrimination thresholds, which they did not (see Fig. 7).

The assumption that the mask interrupts processing in the separation discriminator has another testable implication. Within the local spatial filters, the effect of the mask is the same for separation discrimination and bisection, because the stimuli are locally similar. However, if the separation discriminator operates serially, as the sequential-processing model asserts,

then for a given exposure duration, the mask should have a different effect for bisection, which requires two separation discriminations, than for separation discrimination, which requires only one within that duration. We tested this prediction experimentally.

Methods

Separation-discrimination and bisection thresholds were measured for a 2.8° separation using a 33-ms exposure duration without a mask for comparison with our previous data (obtained on the same observer) with a mask. Test contrast was set to three times the detection threshold (obtained without a mask). We also obtained data using a 500-ms exposure duration with test contrast set to 45% for both the masked and unmasked conditions. Each datum is based on at least 420 trials. All other conditions of the experiment were the same as in the previous separation-discrimination and bisection experiments.

Results

The results of the 33-ms exposure duration experiments are shown in Fig. 10. When no mask was used (open bars), there was little difference between the thresholds for bisection and separation discrimination. Separation-discrimination thresholds were only slightly higher. However, when the mask was used (lined bars), task had a large effect: the bisection threshold was twice as high as the separation-discrimination threshold for the same condition. The data for a 500-ms exposure duration, which are not shown, yielded no effect of mask for either task.

The interaction between the task and the effect of the mask, evident in the data of Fig. 10, implies that the primary effect of masking is to terminate processing within the separation discriminator (because the effect of the mask within the local spatial filters is independent of task). The factor-of-2 difference between the bisection and separation-discrimination thresholds in the masked condition might be occurring because the observer acquires only one separation in the 33-ms presentation time and compares this separation to a remembered mean separation. (We have seen above that comparison to this remembered mean is almost as accurate as comparison to a presented mean.) The results of this experiment indicate that masking is indeed occurring within the separation discriminator. Thus, these results support the sequential-processing model of bisection.

The data on the effect of a mask also tell us something else of importance: The separation discriminator does not depend on the presence of the target for continued processing. Bisection thresholds equaled separation-discrimination thresholds with the 33 ms unmasked target even though 33 ms is not long enough for the separation discriminator to process two separations accurately. Apparently if there is no masking stimulus, input to the separation discriminator continues well after the stimulus itself has been extinguished.

SUMMARY AND DISCUSSION

We found that exposure duration had a different effect on bisection thresholds than on separation-discrimination thresholds.

Bisection thresholds decreased more between 33 ms and 150 ms than did separation-discrimination thresholds. This difference was accounted for by a model in which bisection is done by encoding the two separations sequentially. This sequential-processing model of bisection was further supported by data showing that the effect of exposure duration on separation-discrimination and bisection thresholds could not be attributed to temporal contrast integration. The sequential-processing model relies on a definition of the bisection threshold that assumes that the observer compares the two separations created by the three lines in the bisection stimulus. Direct comparison of bisection and separation-discrimination thresholds supported this definition. Also consistent with our model, we found that the primary effect of a mask in our high-contrast conditions was to interrupt extraction of information about the separation between the targets, not to interrupt processing of the individual targets.

The spatio-temporal interaction was not specific to the large separation condition. The data obtained using an 11′ separation exhibited the same general properties as did those obtained using a 2.8° separation.

The data for the two conditions differed significantly at long durations: exposure duration continued to have an effect for durations between 150 and 500 ms for the small separation but not for the large. Also, contrast had a larger effect for the small separation than for the large. The difference in exposure-duration effects for large and small separations has been reported previously (Burbeck, 1986; Yap, Levi, and Klein, 1987). Burbeck argued that the difference is attributable to differences in the

temporal characteristics of the relevant local spatial filters: The local spatial filters that detect the individual targets are smaller for small separations than for large ones, and smaller local spatial filters have longer temporal integration times. The temporal integration that occurs within the local spatial filters is contrast integration, so this explanation of the exposure-duration effect predicts that contrast should also have more effect at small separations than it does at large separations, which was what we found.

The spatio-temporal interaction was remarkably similar for the large and small separations. The small differences that did exist were consistent with previous findings and conclusions. The data did not support the idea that separation judgments for small separations are mediated by a different mechanism than for large ones. Specifically, the data did not support the theory that small separations are encoded directly by the local spatial filters, as has been proposed (Wilson and Gelb, 1984; Klein and Levi, 1985, 1987; Yap, Levi, and Klein, 1987, 1989; Levi, Klein, and Yap, 1988).

Sequential processing has previously been observed in another spatial-position task. Meer and Zeevi (1985) measured thresholds for detecting the nonalignment of a dot relative to the virtual intersection of a horizontal and vertical line. They found that a short exposure duration (200 ms) results in a high threshold, and a long exposure duration (2000 ms) results in a hyperacuity threshold, whereas for a single alignment task, there is no exposure-duration effect. They concluded that the two alignment judgments occur sequentially. Analogously, we have been able to

conclude that the two separation judgments in bisection occur sequentially.

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Figure Captions

Figure 1 Schematic diagram illustrating the temporal and spatial configurations used in the initial bisection and separation-discrimination experiments.

Figure 2 Thresholds for separation discrimination and bisection as a function of exposure duration for two separations, 2.8 deg and 11 minarc. Data were obtained for three observers. Where no error bar is evident, the extent of error is smaller than the symbol.

Figure 3 Thresholds for separation-discrimination and bisection normalized to the 33 ms threshold value, plotted as a function of exposure duration. Error bars are not shown.

Figure 4 Comparison of separation-discrimination thresholds with bisection thresholds that have been shifted to the left along the horizontal axis by a factor of 2. Error bars are not shown.

Figure 5 Comparison of separation-discrimination and bisection thresholds after each has been transformed according to the sequential-processing model. The bisection thresholds have been shifted to the left by a factor of 2 and the separation-discrimination thresholds have been reduced by the 250-ms-residual difference, Δ_{250}. Error bars are not shown. See text for a detailed explanation.

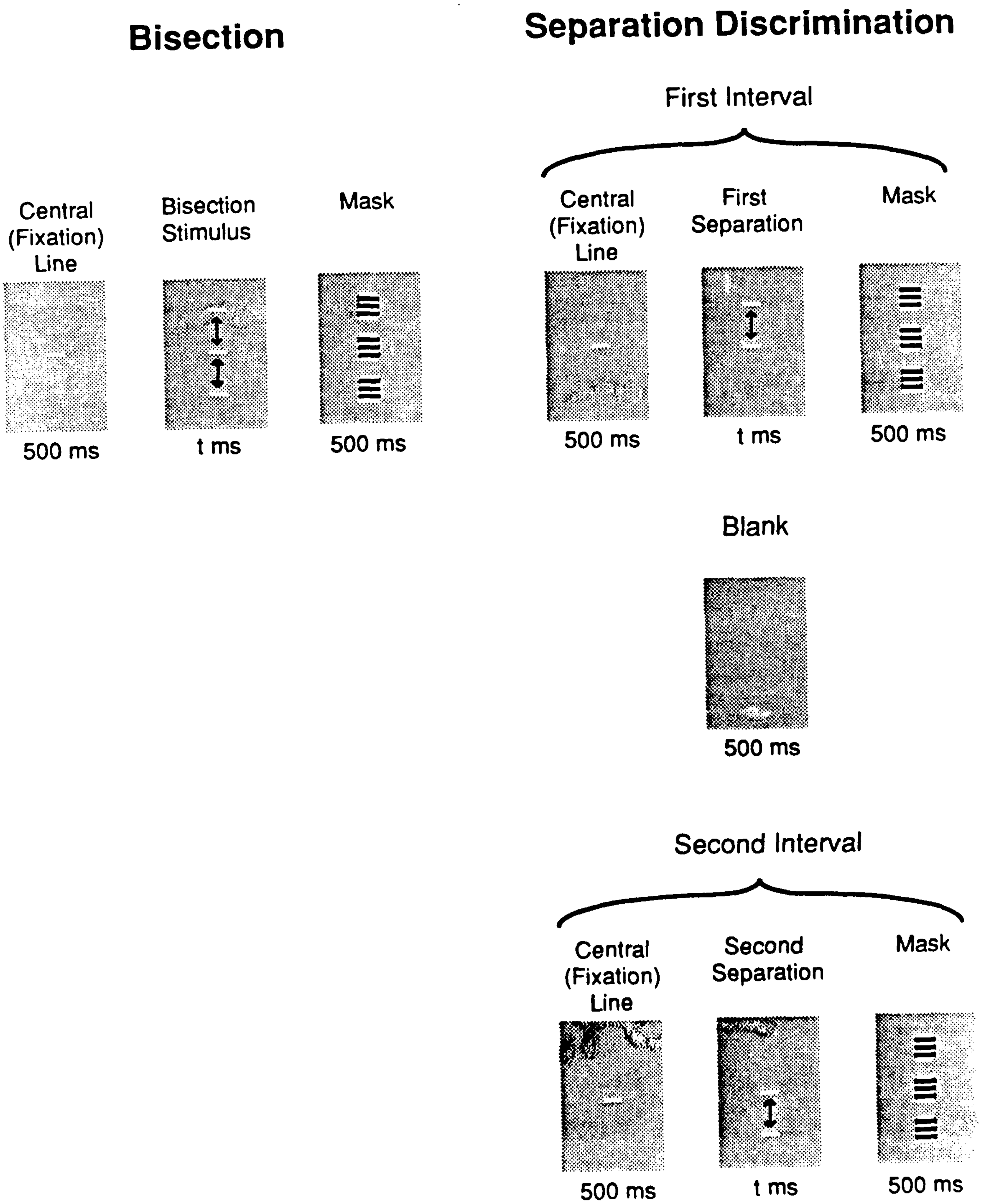
Figure 6 Contrast-detection thresholds for the line stimuli used in the first experiment, measured as a function of exposure duration.

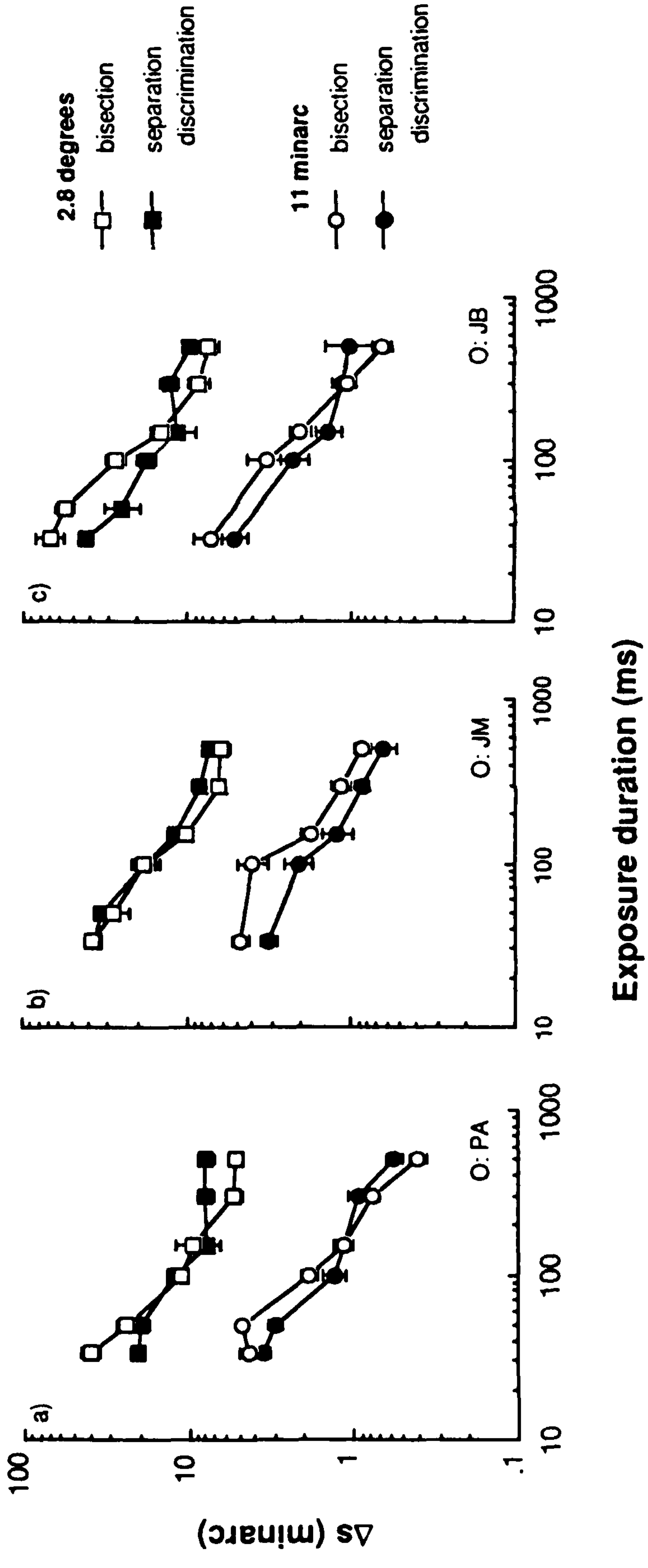
Figure 7 (a) Separation discrimination and bisection thresholds for two separations measured as a function of exposure duration. The effective contrasts of the stimuli were equated by making the stimulus contrasts equal to a constant multiple of the detection threshold for that duration and separation. (b) The same separation discrimination and bisection thresholds after being transformed according to the sequential-processing model. (c) Bisection thresholds plotted as a function of exposure duration using higher contrast stimuli for the 2.8 deg separation. Error bars do not show because they are smaller than the symbols.

Figure 8 Schematic illustration of the effect of moving one line by Δs for two bisection and one separation discrimination stimuli. In each case the line-target has been displaced upwards.

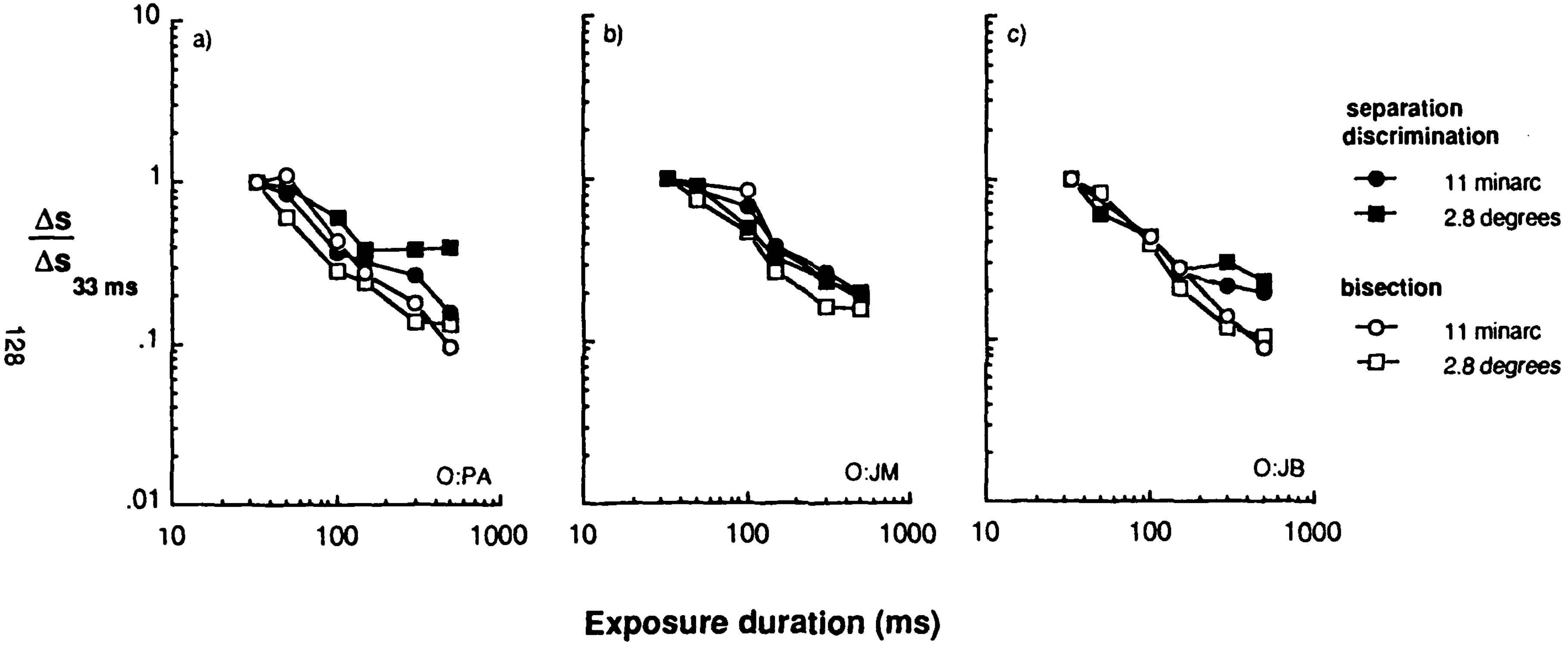
Figure 9 Thresholds for two bisection tasks and a separation-discrimination task. In bisection$_m$ the position of the middle line-target was changed while in bisection$_t$ the position of the top line-target was changed. The threshold shown corresponds to the extent of displacement of one line-target for all three tasks, regardless of the effect on the separation. The solid line corresponds to half the separation-discrimination threshold.

Figure 10 Effects of presenting a mask at the termination of a briefly flashed (33 ms) stimulus in bisection and separation discrimination. Stimulus separation was 2.8 deg. Target contrast was set to three times the detection threshold for each condition (33% and 36% for the unmasked and masked stimuli respectively).

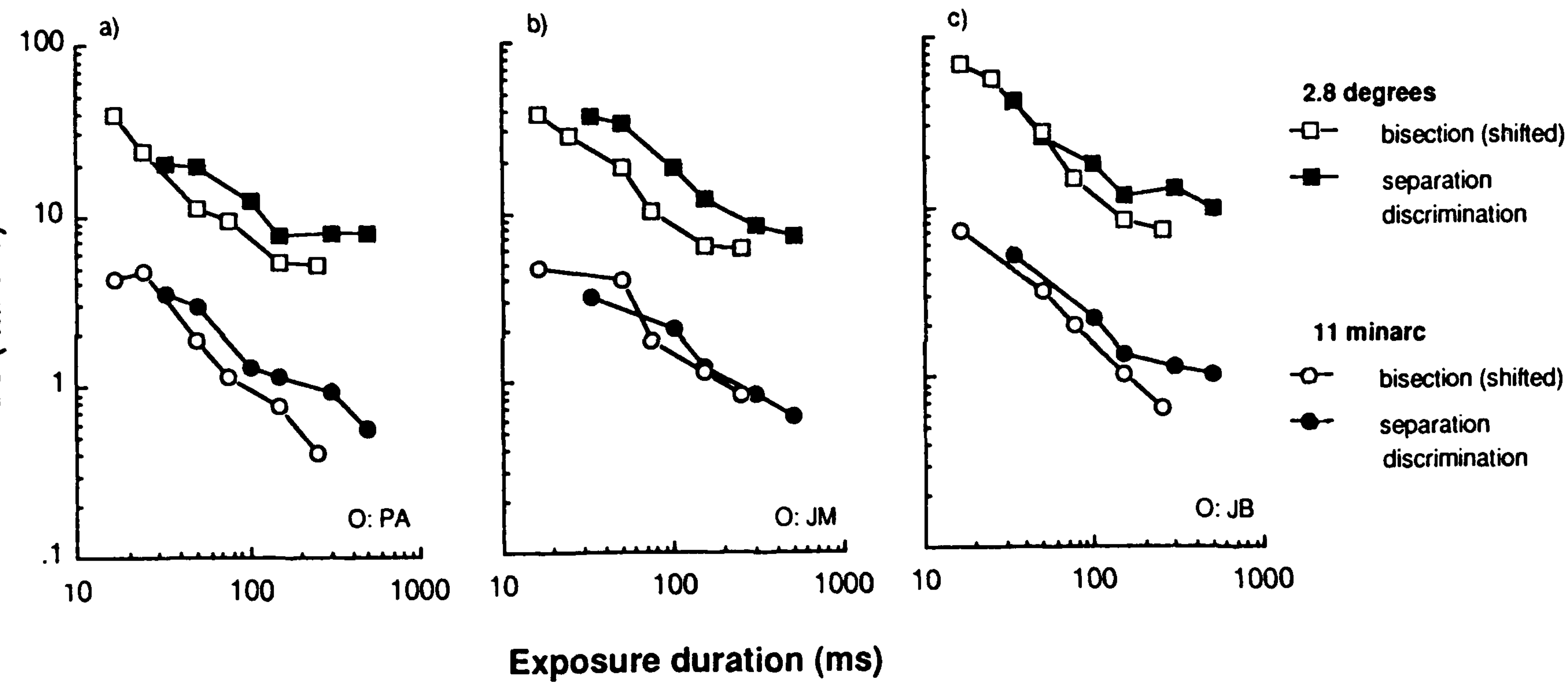

Bisection
Central (Fixation) Line
500 ms
Bisection Stimulus
t ms
Mask
500 ms
Separation Discrimination
First Interval
Central (Fixation) Line
500 ms
First Separation
t ms
Mask
500 ms
Blank
500 ms
Second Interval
Central (Fixation) Line
500 ms
Second Separation
t ms
Mask
500 ms

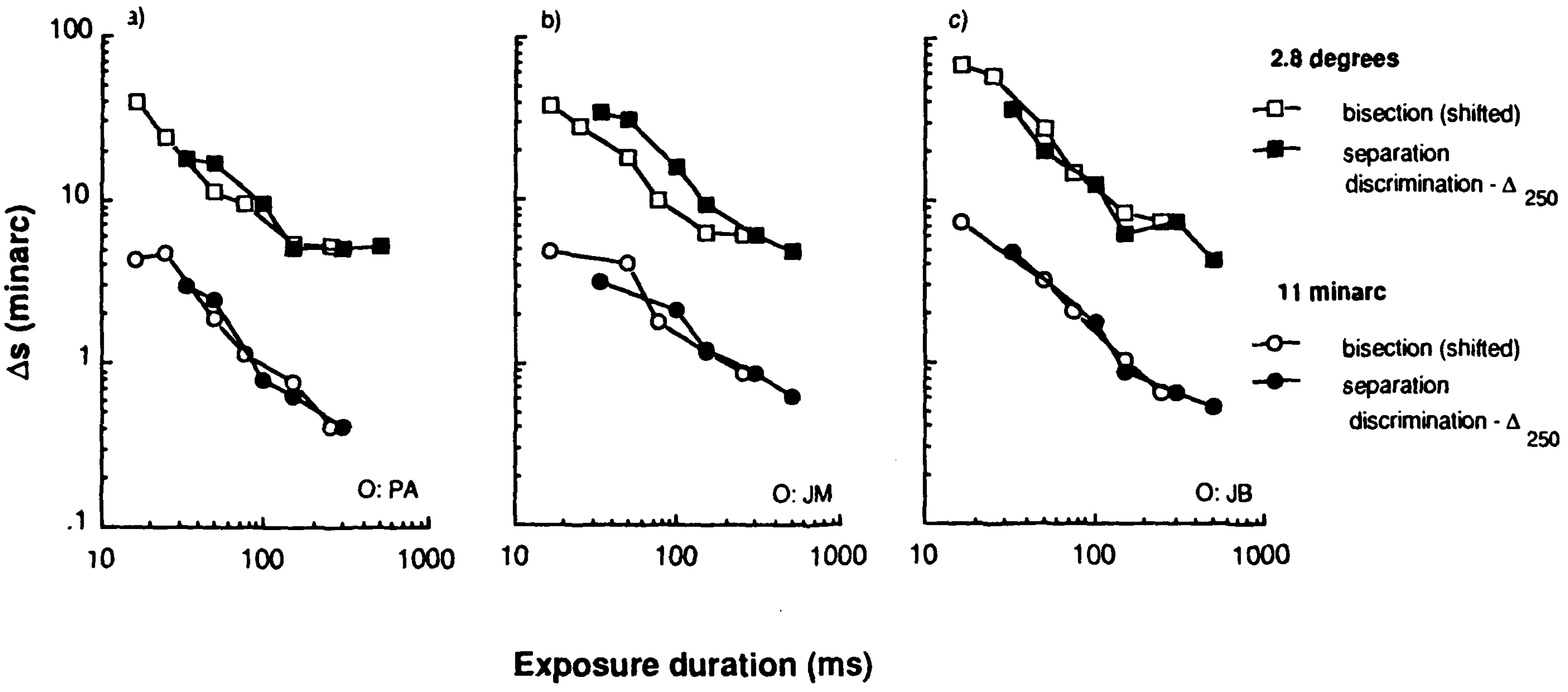


2.8 degrees
bisection
separation discrimination
11 minarc
bisection
separation discrimination
Δs (minarc)
100
10
1
.1
10
100
1000
a)
b)
c)
O: PA
O: JM
O: JB
Exposure duration (ms)

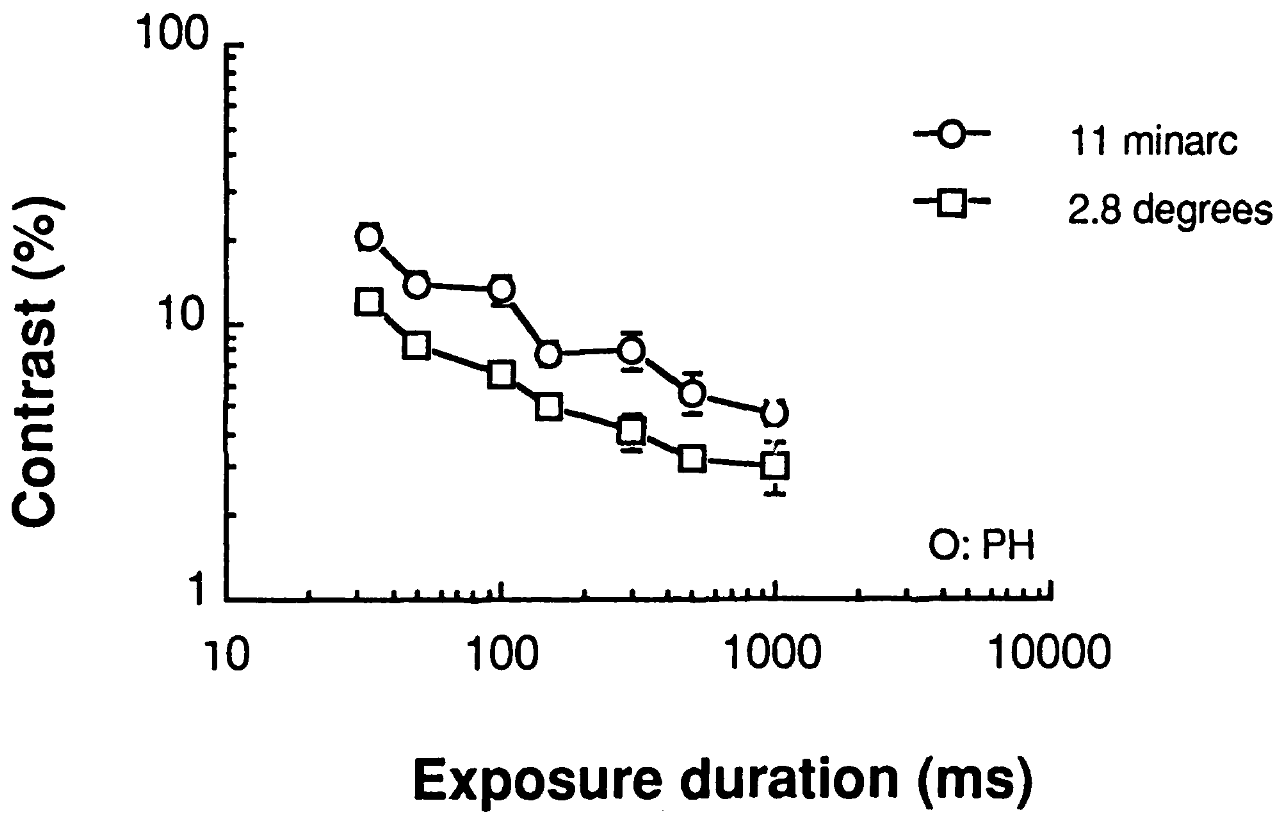


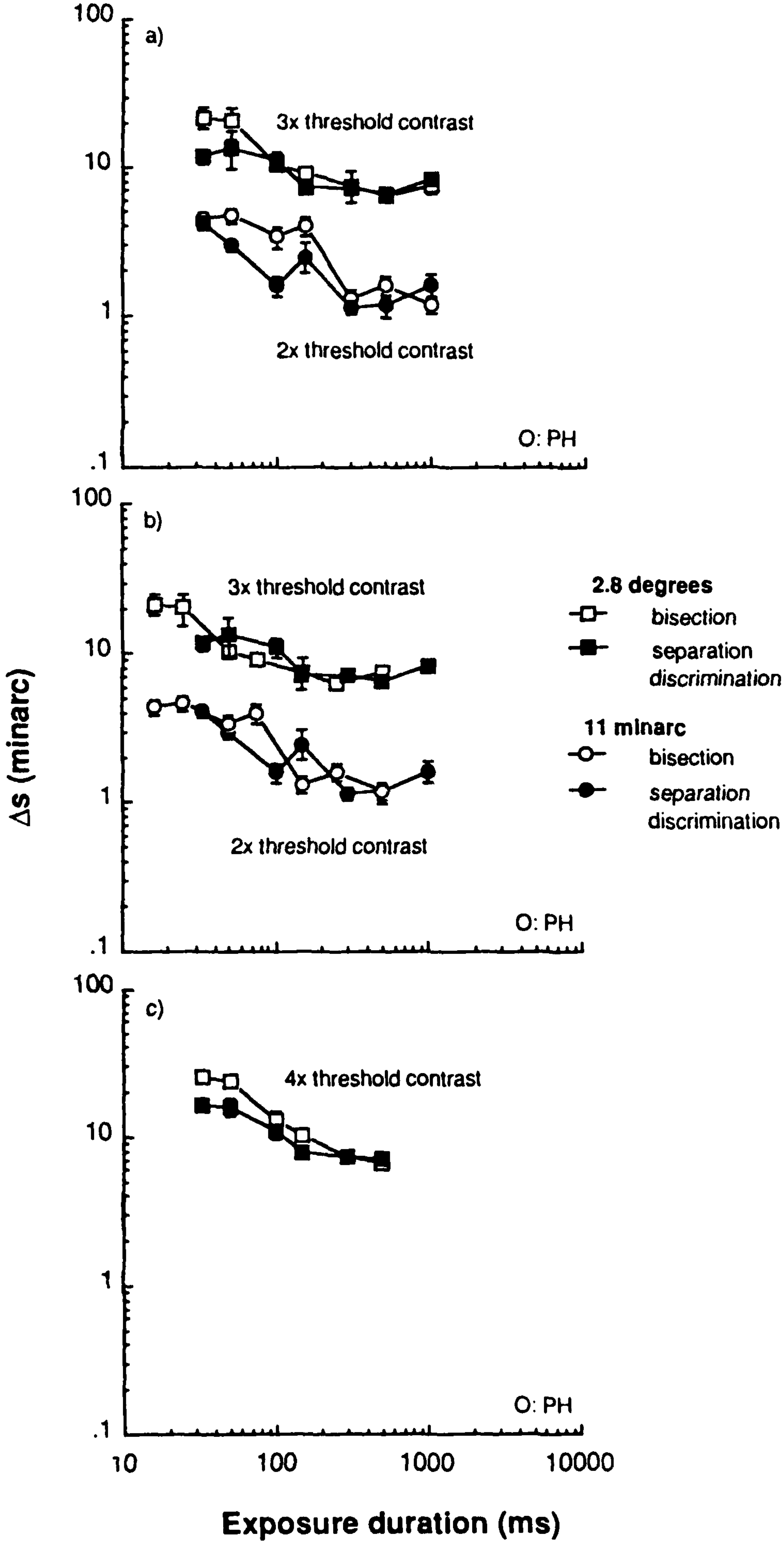
a)
b)
c)
10
1
.1
.01
10
100
1000
O:PA
O:JM
O:JB
separation discrimination
11 minarc
2.8 degrees
bisection
11 minarc
2.8 degrees
$\frac{\Delta s}{\Delta s_{33\ ms}}$
Exposure duration (ms)

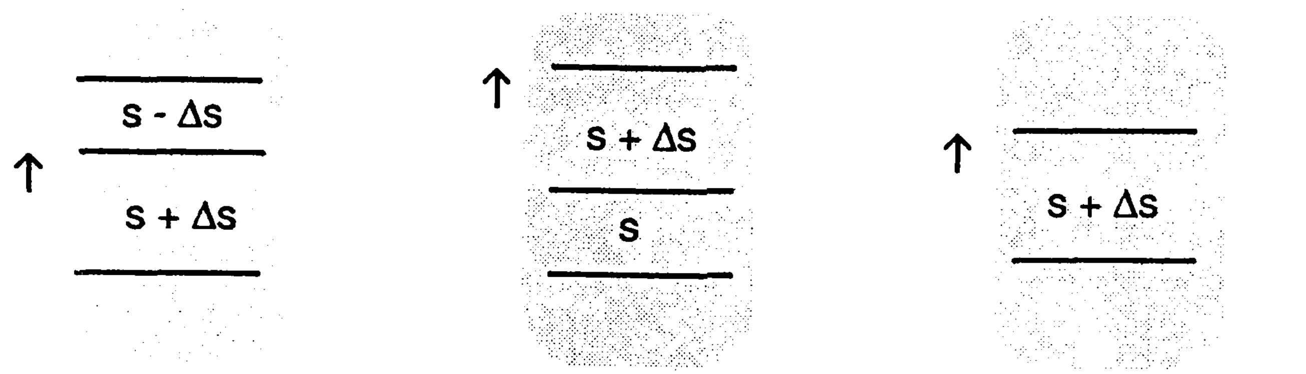

a)
b)
c)
100
10
1
.1
Δs (minarc)
10
100
1000
O: PA
O: JM
O: JB
Exposure duration (ms)
2.8 degrees
bisection (shifted)
separation discrimination
11 minarc
bisection (shifted)
separation discrimination



a)
b)
c)
100
10
1
.1
10
100
1000
Δs (minarc)
Exposure duration (ms)
O: PA
O: JM
O: JB
2.8 degrees
bisection (shifted)
separation
discrimination - Δ 250
11 minarc
bisection (shifted)
separation
discrimination - Δ 250


100
10
1
10
100
1000
10000
Contrast (%)
Exposure duration (ms)
11 minarc
2.8 degrees
O: PH

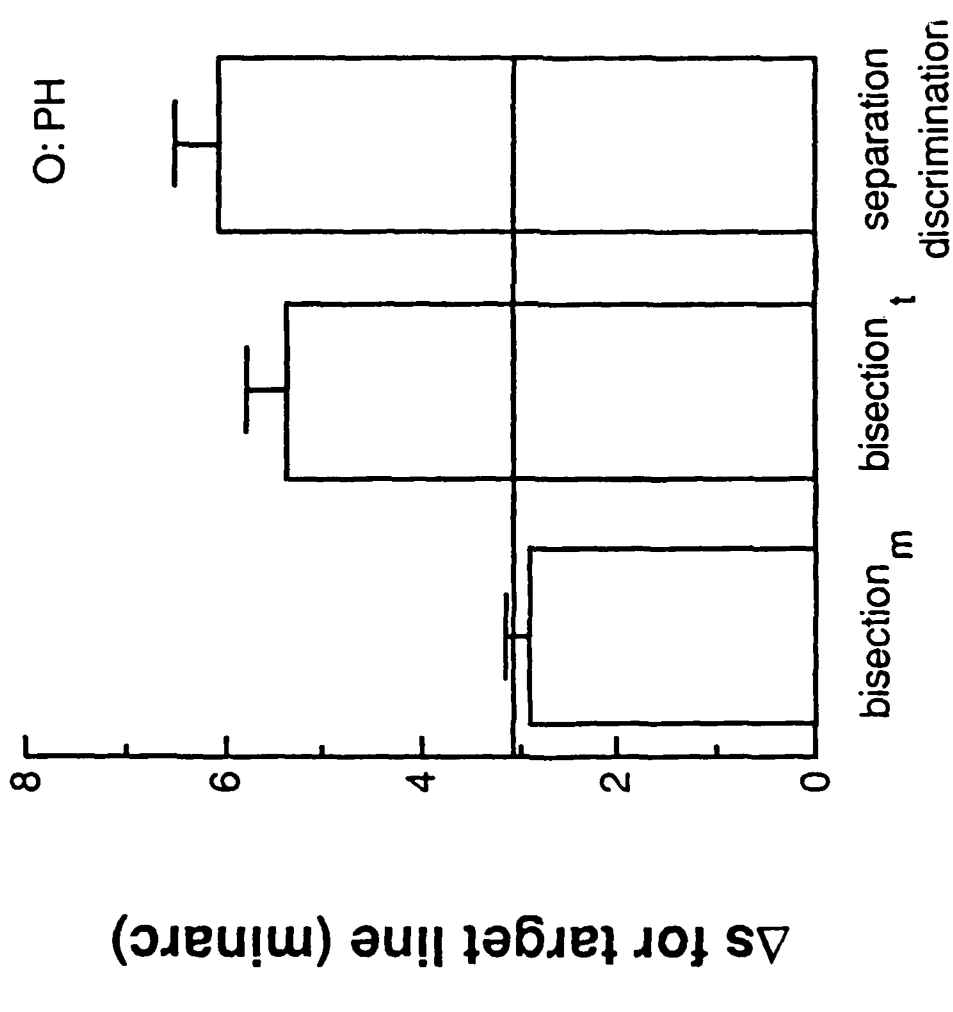

a)
3x threshold contrast
2x threshold contrast
O: PH
b)
3x threshold contrast
2x threshold contrast
O: PH
2.8 degrees
bisection
separation discrimination
11 minarc
bisection
separation discrimination
c)
4x threshold contrast
O: PH
100
10
1
.1
10
100
1000
10000
Δs (minarc)
Exposure duration (ms)



$s-\Delta s$ vs $s+\Delta s$ — **Bisection**$_{\text{middle}}$

$s+\Delta s$ vs s — **Bisection**$_{\text{top}}$

$s+\Delta s$ vs s_{mean} — **Separation Discrimination**


O: PH
Δs for target line (minarc)
0
2
4
6
8
bisection m
bisection t
separation discrimination
Task

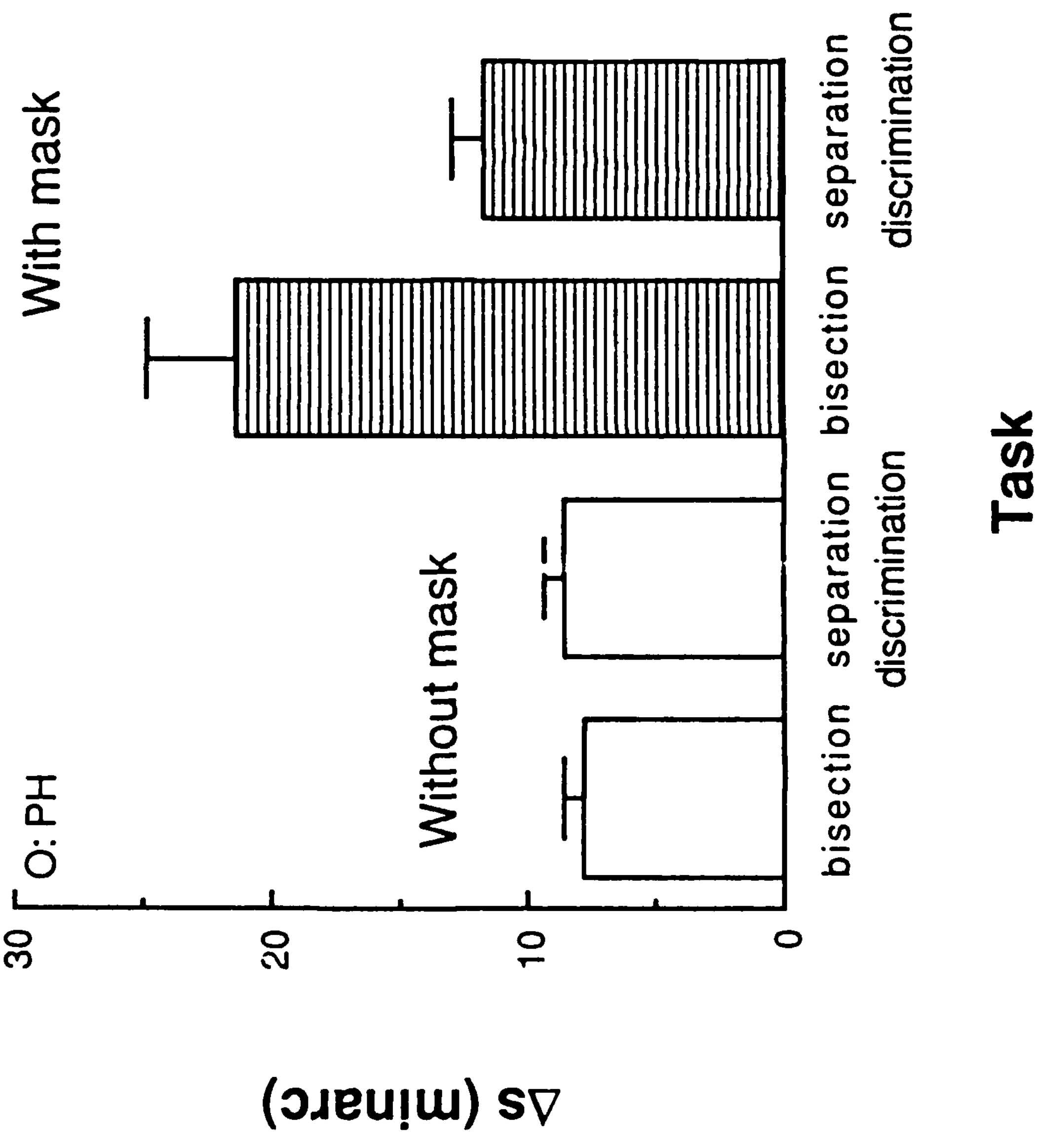

O: PH
Without mask
With mask
bisection
separation discrimination
bisection
separation discrimination
Task
Δs (minarc)
0
10
20
30

Table 1 Lists of studies using each of the two definitions of the bisection threshold. The comparison-to-inferred-center threshold is a factor of 2 smaller than the comparison-between-separations threshold.

Comparison to Inferred Center	Comparison Between Separations
R. Fischer, 1891 (as cited by Wolfe,1923)	Volkmann, 1857 (as cited by Fechner,1860)
Wolfe, 1923	R. Fischer, 1891 (as cited by Wolfe,1923)
Bedell, Johnson, & Barbeito, 1985	Andrews & Miller, 1978
Levi & Klein, 1983	Burbeck, 1987
Klein & Levi, 1985, 1987	Present study
Levi, Klein, & Yap, 1987, 1988	
Toet, van Eekhout, Simons, & Koenderink, 1987	
Yap, Levi, & Klein, 1987 a,b	
Toet & Koenderink, 1988	
Lindblom & Westheimer, 1989	

Appendix E

SPATIAL INTERACTIONS IN RAPID PATTERN DISCRIMINATION

Spatial interactions in rapid pattern discrimination

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Abstract—We measured reaction times (RTs) for identification of a target among distracters under stabilized image conditions in which the positions of the target and the distracters were constant within a single experimental session. Under these conditions, the observer need not search for the target because its position is known. We nevertheless found that the presence of even a single distracter could elevate RTs. The magnitude of this effect depended on the distance of the distracter from the target and, for some observers, the distance of the distracter from the fovea. When we added not one but six background elements in a ring around the target, RT increased even more. If, apart from these neighboring distracters, the target was surrounded by more distracters located beyond the nearest neighbors, RT was, in general, not increased further. These findings suggest that adding background elements in a search task can elevate RTs in ways that are not dependent on the positional uncertainty of the target.

INTRODUCTION

Reaction time (RT) procedures have been widely used to study the detectability of a target element in a display of nontarget elements. Specifically, experiments often measure RT as a function of the number of elements in the field, under the assumption that if RT increases with increasing number of elements, then the observer has engaged in a serial search, whereas if there is no such increase, then the elements have been processed in parallel (Treisman and Gelade, 1980; Bergen and Julesz, 1983; Pashler, 1987; Wolfe *et al.*, 1988). This interpretation is supported by the finding that target detectability improves substantially if the observer knows in advance the location of the target, suggesting that the observer is able to direct his attention and process information from this location selectively (Engel, 1971; Eriksen and Hoffman, 1972; Posner, 1980; Kröse and Julesz, 1989).

Complicating this interpretation, however, is the finding that even if the target is presented at a fixed position, so that no 'search' is necessary, the addition of more background elements can influence target detectability (Eriksen and Eriksen, 1974). Eriksen and Eriksen (1974) measured RTs for the identification of a target letter (always presented 0.5 deg above the fixation point) which was flanked by noise letters (3 left, 3 right) and found RTs elevated by the presence of the noise letters. More specifically, they found effects of target-noise similarity and of the between-letter spacing, for spacings up to about 0.5 deg. Whatever mechanism orients attention to the expected location of the target is apparently not able to ignore completely the activity at the nontarget locations. The experiments reported here examine the effects

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of such distracters with a peripherally located target. Our specific aim was to get a sense of the magnitude and extent of these distracter effects for a nonfoveal target, as compared to the results reported in the literature for a foveal target, looking in particular at the effect of the spacing between the target and the distracter and the effect of the retinal position of the distracter.

Bouma (1970) previously studied lateral interactions in the identification of a peripherally presented letter (between 1.5 and 10 deg eccentricity). His results show that the size of the area within which noise letters (1 left, 1 right) interact is approximately equal to 0.5 times the eccentricity at which the target is presented. However, in his experiments there was uncertainty about the target position; the target could occur either to the right or to the left of the fixation point. Because the observer could not attend to a single retinal location, the data from his experiments may exaggerate the magnitude of the interactions.

In our experiments, the target was always presented at a fixed location (3 deg above the fovea). Image stabilization was used to ensure consistent target placement without requiring the observer to foveate a fixation mark. This is important because deliberate foveation requires attention, and we wanted the observer to attend to the target location, not the fovea. This technique is also preferable, for our purposes, to the use of a visual cue with multiple possible locations, because the cue itself draws attention, and we wished to determine the extent to which the observer could direct his attention without a visual trigger, as he must do if he is searching for a target.

METHODS

Stimuli were presented on a Macintosh Plus computer (Apple Computer Inc.), which also served to measure RTs and percentage of errors. The stimuli were stabilized on the retina by an SRI Dual-Purkinje Eyetracker, Generation V, with stimulus deflector (Crane and Clark, 1978; Crane and Steele, 1985). All experiments were conducted with stabilized images.

The target and distracter elements were either $\cup$s or $\cap$s, 0.47 deg in height and 0.30 deg in width. They were white (equal to the luminance of the background) and were presented on dark disks. Each disk subtended 0.78 deg of visual angle. These elements were similar to the ones used by Julesz *et al.* (1973) and have the property that a texture field composed of $\cup$s can not be discriminated effortlessly from a texture field composed of $\cap$s. See Figs. 1, 3, and 4 for examples of the stimuli. The mean luminance of the background was approximately 140 $cd.m^{-2}$, maintaining photopic conditions. The background subtended 9.8×18.8 deg at the 50.5-cm viewing distance (measured from the second servo-driven mirror of the stimulus deflector, which is optically conjugate with the pupil).

The target was always presented in the same spatial position, 3.1 deg above the fovea on the vertical meridian. The stimuli came on abruptly and remained on until the observer responded. No fixation mark was needed during the experiments because the stimulus was stabilized on the retina. The target was present on every trial and the observer had to report, as rapidly as possible (while maintaining a constant low level of errors), whether he (or she) saw a $\cup$ or a $\cap$ by pressing one of two keys on a keyboard. Depending on the experimental condition, one or more distracters could be presented simultaneously with the target. The number and positions of the distracters were constant during a single experimental session. The observer

distinguished the target from the distracters only by its position. Each distracter was randomly and independently chosen to be a ∪ or a ∩ on each trial.

A block consisted of 110 trials. The RTs of the first 10 trials of each block were not used in calculating the average, but served as a brief practice. After eliminating the trials in which an incorrect response was given, we calculated the geometric mean RT of all trials in the block, regardless of whether a ∪ or a ∩ served as the target. Extensive practice was done before collecting any of the data included in the main body of this report. The results of the practice sessions are shown in Appendix A.

Before each block of trials, a fixation point was presented in the center of the display. The observer adjusted the offset of the stimulus deflector to make this fixation point coincident with his center of gaze (and, we assume, coincident with the center of his fovea). The fixation point disappeared prior to the first trial and did not return until the end of the last trial in the block, when the observer confirmed that it still coincided with his center of gaze. (It always did.)

Care was taken to randomize the order in which data were collected for the different conditions, in case there were residual learning effects. In addition, we measured RT for the *no-distracter* condition several times each day and used that as the baseline for that day's data. (Preliminary experiments showed that RTs fluctuate from day to day even after the initial learning period is over. See Appendix A.) Performance is expressed as the difference between the RT with distracter(s) and the average no-distracter RT for the day. Data were obtained from at least three 110-trial blocks for each condition, unless indicated otherwise.

TARGET-DISTRACTER SPACING AND RELATIVE POSITION

We measured RT with and without a single distracter. The distracter was placed at one of six positions at one of five distances from the target. The six distracter positions used in the experiment are shown in Fig. 1, where a distracter is placed at Position 1 as an example. The position of the target was fixed. The position of the distracter was fixed during an experimental session and was varied between sessions. We found that RTs obtained with background elements to the left of the target were, in general, not significantly different from RTs obtained with background elements to the right

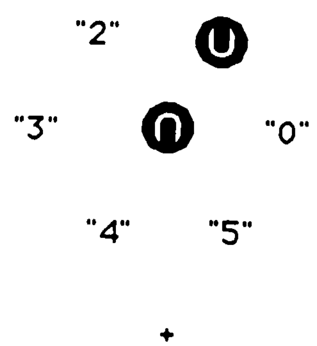

Figure 1. Positions of distracter used in single-distracter experiments. In this example, the distracter is presented at Position 1. The target (∩ in this illustration) was always in the same location. The small cross, which was not visible during the trials, is the fixation point.

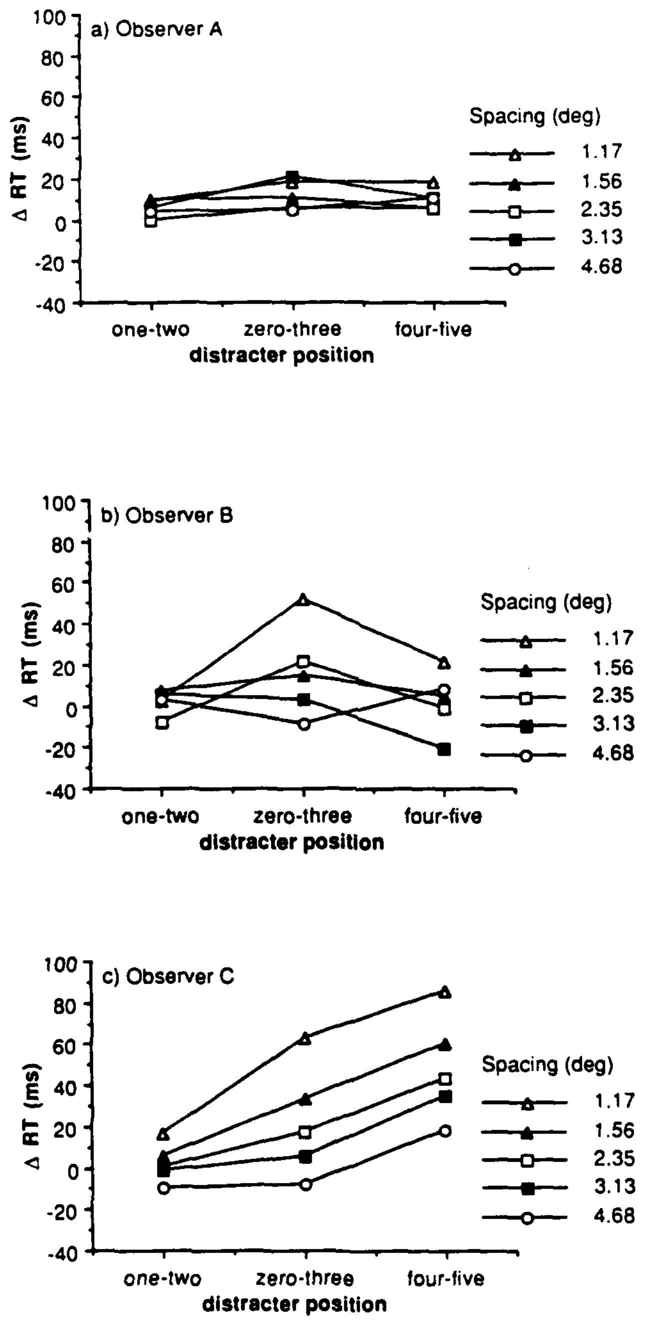

Figure 2. Change in RT caused by the presence of a single distracter (which could be a ∪ or a ∩). Data are shown for three observers and a range of target-distracter spacings. Distracter positions refer to the naming scheme shown in Fig. 1.

of the target. Therefore, the data were averaged across the left and right positions. Positions 1 and 2 are above the target and have a larger eccentricity than the target; Positions 0 and 3 are beside the target and have a similar eccentricity; and Positions 4 and 5 are below the target and have a smaller eccentricity.

Results for three observers are shown in Fig. 2. Observer B was tested on 4 blocks per condition, Observers A and C, three blocks per condition. The vertical scale is the same for all observers to facilitate comparison across observers.

There are large and consistent intersubject variations in the effect of a single distracter. Observer A is less sensitive to a distracter than are Observers B and C. A two-way (position × spacing) analysis of variance (ANOVA) applied to the data of Observer A shows that the effect of position is not significant [$F(2, 75) = 1.25$, $P > 0.25$] and that the effect of spacing is also not significant [$F(4, 75) = 1.52$, $0.10 < P \leqslant 0.25$]. However, for Observer B, both the effects of position [$F(2, 105) = 3.96, 0.01 < P \leqslant 0.025$] and spacing [$F(4, 105) = 4.37, 0.0001 < P \leqslant 0.005$] are significant. For Observer C, the effects of spacing and position are even more prominent [effect of position, $F(2, 75) = 17.5$, $P \leqslant 0.001$; effect of spacing, $F(4, 75) = 8.28$, $P \leqslant 0.0001$].

For Observer C, who showed the largest effects, a distracter placed below the target (i.e. nearer the fovea) has a larger effect than does one next to or above the target. This is consistent across spacings and is not attributable to the order of presentation, which was randomized. This pattern, together with the natural association between attention and foveation, suggested the following experiment in which we examined the effect of the retinal position of the distracter.

RETINAL POSITION OF DISTRACTER

Although the background elements at Positions 4 and 5 (Fig. 1) are near the fovea for spacings of 2 or 3 deg, they are never closer than 1.5 deg to the center of the fovea. To get more information on the effect of a foveal distracter and to determine the effects of the retinal positions of the distracters more systematically, we used a different set of positions. Spacing between the target and distracter was fixed at 3.1 deg. Distracter position was varied from $\phi = 0$ deg, distracter to the right of the target, to $\phi = -180$ deg, distracter to the left of target, in seven equally spaced steps along an equidistant arc below the target, as shown in Fig. 3a. At $\phi = -90$ the distracter is presented at the fovea. Results are shown in Fig. 3b for four observers: Observers A and B, who participated in the previous experiment and two other observers who were also experienced at this type of task. Observer D was tested an 3 blocks per conditions, Observers A and E, 4 blocks each, and Observer B, 5 blocks per condition. The number of blocks used depended on the variability of the observer's responses.

For Observers D and E, a single background element located on or near the fovea had a large effect on RTs. The analysis of variance on the effect of position shows that this effect is significant for both observers: Observer D [$F(6, 14) = 10.1, 0.0001 < P \leqslant = 0.005$] and Observer E [$F(6, 21) = 2.97, 0.025 < P \leqslant 0.05$]. An increase in RT also occurred for Observer B, but the effect was relatively small and not significant (effect of position [$F(6, 28) = 1.56, P > 0.25$]. For Observer A, there was no significant increase in RT for the foveally-presented distracter [effect of position, [$F(6, 21) = 1.49, 0.1 < P < 0.25$]. The lack of effect for Observers A and B was not caused by long RTs in the no-distracter condition. Observer A, who showed the least

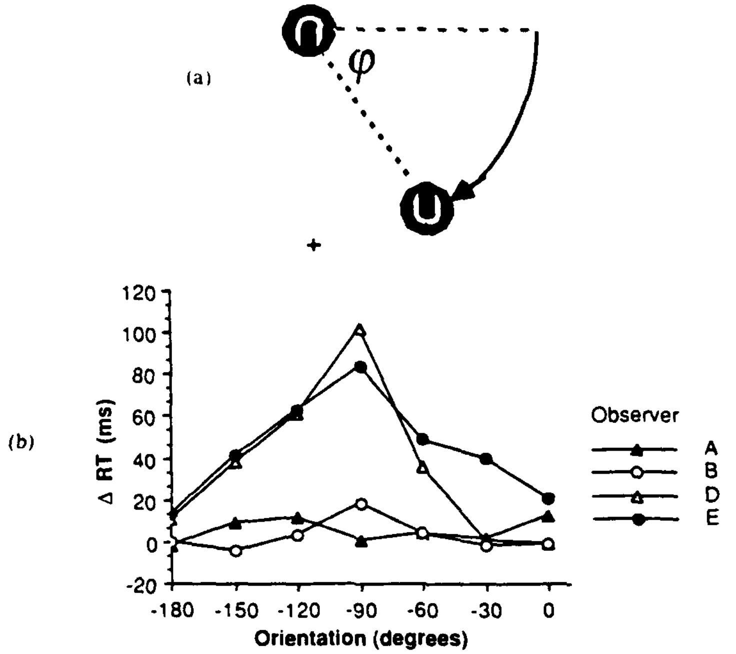

Figure 3. (a) Schematic diagram of position of distracter relative to target. The distracter was presented at a constant distance of 3.1 deg from the target at various angles. At −90 deg orientation, the distracter was on the observer's fovea. (b) Change in RT caused by the presence of the distracter, as a function of distracter position. Data are shown for four observers.

effect of the single distracter, had the shortest RTs of all observers (mean no-distracter RT of 435 ms). Thus, there appear to be large systematic inter-observer differences in the effect of a distracter presented foveally. For some observers, a distracter placed on the fovea is much more distracting than one placed off of the fovea; for others, it has no preferential effect. This difference was not immediately attributable to any other characteristics of the observers.

SURROUNDING THE TARGET WITH DISTRACTERS

To learn more about the effect of increasing the number of distracters, we surrounded the target element by background elements, as shown in Fig. 4. There were either six background elements, arranged in a hexagonal 'one-ring' configuration around the target as shown in Fig. 4a, or eighteen background elements arranged in a 'two-ring' configuration, as shown in Fig. 4b. Reaction times for identification of the target, whose position was always known, were measured and compared to the no-distracter condition. The spacing of the target-distracter array was a parameter of the experiment. With a hexagonal arrangement, the distance between any two adjacent elements is constant for a given spacing; thus, for example, a spacing of 1.2 deg means that the distance between any element (target or distracter) and its nearet neighbor was 1.2 deg.

The number of background elements (6 or 18) and the spacing were kept constant during a block (110 trials). RTs for the 'one-ring' condition were measured for spacings

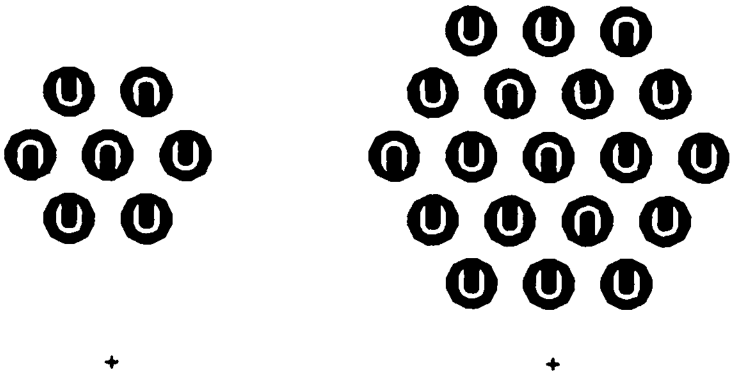

Figure 4. The target element (∩ in this example) surrounded by either one or two rings of distracters (∩s and ∪s). The small cross shows where the subject fixated (the cross was not present during the trials). Fixation accuracy was ensured by image stabilization.

ranging from 1.2 to 4.8 deg. RTs for the 'two-ring' condition were measured for spacings from 1.2 to 2.4 deg because of limitations imposed by the display size. Observers A and C were tested on 3 blocks of trials, and Observer B on 4 blocks.

The results are shown in Fig. 5, where we plot the increase in RT as a function of spacing for the one- and two-ring conditions. As a comparison, we also show the maximum RT elevation obtained on the one-distracter condition (as reported in Fig. 2).

For Observer A, RT is elevated only slightly by the rings of distracters. For Observer B, RT is significantly elevated by the rings, even at large spacings. For Observer C, RTs are elevated markedly by the rings at small spacings and are elevated somewhat at large spacings. For all three observers, the rings at small spacings produce the largest ΔRTs. These effects are always larger than the maximum ΔRTs produce with a single distracter.

The effect of adding six background elements instead of one is small for Observer A, consistent with the small effects obtained for her with a single distracter. However, the effect of the ring is large for the other two observers. A two-way ANOVA (number of distracters × spacing) applied to the data for spacings less than 2.4 deg, shows for Observer A [$F(1,35) = 0.516, P > 0.25$], Observer B [$F(1,50) = 19.2, P \leqslant 0.0001$], and for Observer C [$F(1,35) = 10.9, 0.0001 < P \leqslant 0.005$]. The effect of spacing (a two-way ANOVA, condition × spacing) is significant for all three observers: Observer A [$F(2,27) = 2.96, 0.05 < P \leqslant 0.10$], Observer B [$F(2,39) = 7.25, 0.0001 < P \leqslant 0.005$], and Observer C [$F(6,27) = 20.0, P \leqslant 0.001$]. The effect of adding the second ring (two-way ANOVA, number of rings × spacing, applied to the data for spacings less than 2.4 deg) is not significant for Observers C [$F(1,12) = 0.43, P > 0.25$] and A [$F(1,12) = 1.4, P > 0.25$] but is significant for Observer B [$F(1,18) = 19.99, 0.0001 < P \leqslant 0.005$].

The results of this experiment indicate that adding background elements farther away than the nearest neighbor usually does not affect RT. However, if the number of nearest neighbors is increased from one to six, RTs generally increase.

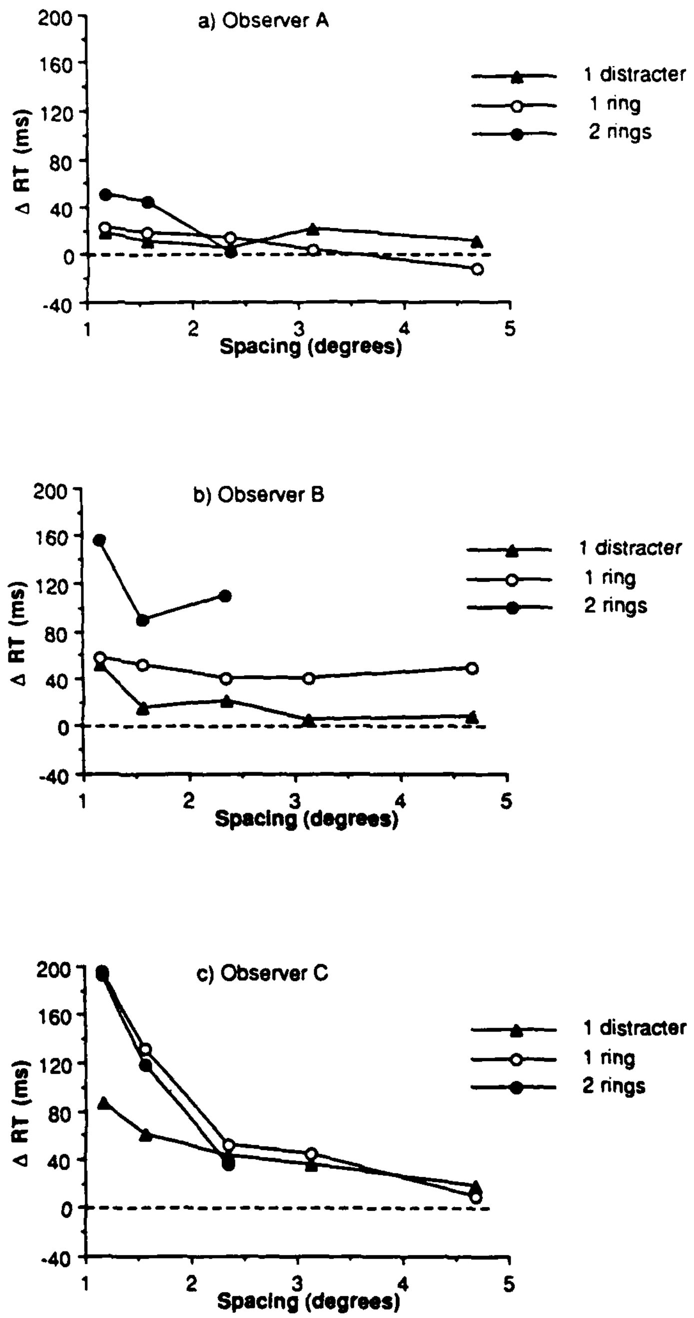

Figure 5. Change in RT caused by the addition of one or two rings of distracters. Also shown for comparison is the maximum ΔRT obtained for each observer and each spacing in the single-distracter condition. See Fig. 2.

DISCUSSION

Even though the target was presented at a fixed retinal position during the entire experiment, so that the observer was certain of its location (both relative to the display edges and absolutely on his retina), there was still a significant effect of the distracters for all except one observer. This effect appears to depend, at least in some observers, on the spacing between the distracters and the target, and on the retinal position of the distracter relative to the fovea.

Results presented in Fig. 2 show that a single background element has at most a small effect if it is presented at a larger eccentricity than the target, even if it is relatively close to the target (1.2 deg was our smallest value). However, a single background element presented at the same (or smaller) eccentricity than the target can have a significant effect, the magnitude of which depends on the spacing between the target and the distracters and on the characteristics of the observer. When this single background element is presented on the fovea, there can be a large increase in RT. The inter-observer variation seen in this effect did not appear to be related to the amount of practice the observer had at this task or to the observer's general level of experience in psychophysical experiments.

Two previous studies have reported effects of distracters that were dependent on the spacing between the distracters and the target. In both of these studies, the exact target location was not known to the observer. In the Bouma (1970) study mentioned above, the target could occur in either of two widely separated locations, so that the observer could not attend to the target location prior to stimulus presentation. Sagi and Julesz (1985) also report spatial interactions of the type seen here, in their study comparing the identifiability of a single target to the discriminability of two targets. They found that the second target masked the first when the two were separated by less than 2 deg for a target eccentricity of 4 deg, and when they were separated by less than 6 deg for a target eccentricity of 12 deg. In their task, the observer had to attend to both targets and the position of the targets varied randomly from trial to trial. In our experiments, the observer knew the target location exactly. Nevertheless, the spatial extent of the interactions we found is not smaller than they found. Thus, knowing the target location in advance does not appear to diminish the extent of the effects.

Lateral effects outside the classical receptive field (CRF) have also been found electrophysiologically. There is increasing evidence that for many visual neurons, stimuli presented outside the CRF strongly and selectively influence responses to stimuli presented within the CRF (for a review, see Allman *et al.*, 1985). For example, a moving background strongly affects the direction and velocity tuning of many cells in the middle temporal area (Allman *et al.*, 1985) and in Areas V1 and V2 (Allman *et al.*, 1988) of the owl monkey. DeYoe *et al.* (1986) have reported analogous surround effects using static texture patterns in Area V1 and V2 of macaque monkeys. In their experiments, texture background often suppressed the response to a target within the CRF, sometimes in an orientation-specific manner. It is unknown whether these interactions are caused by intrinsic connections or by the many descending pathways (Maunsell and Van Essen, 1983) from higher cortical areas.

Such intrinsic connections within a cortical area might account for some of our data, but they do not readily explain the foveal effects we found, which vary profoundly among observers. The effects we observed in our experiments may be nothing else than an involuntary shift of attention, caused by the foveal stimulus. It has been

shown (Kröse and Julesz, 1989) that an invalid cue presented prior to the stimulus may affect performance. Even distracters at a higher eccentricity than the target affect performance if these distracters are presented 40 ms before stimulus onset (Gathercole and Broadbent, 1987). By analogy to distracters that are presented before stimulus onset, it is possible that distracters presented *foveally* may affect the orienting of attention. They are responded to somewhat more rapidly, as shown in Appendix B.

We have shown that even in a nonsearch task, additional background elements can affect discrimination RTs and the magnitude of the effect depends on the positions of these background elements relative to the target and, for some observers, relative to the fovea. When the effect of changing the number of background elements in a search task is used as an argument for serial processing, special attention has to be given to the positions of the target and background elements to distinguish spatial interactions of the type observed here from serial processing.

Acknowledgements

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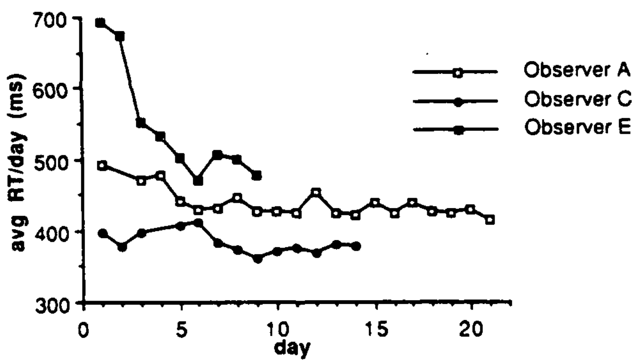
APPENDIX A: EFFECT OF TRAINING

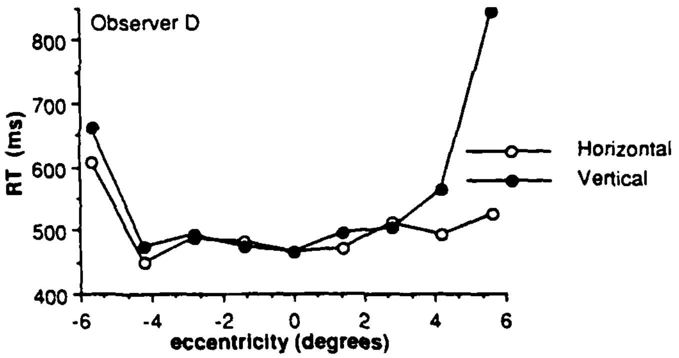
During the experiments, substantial learning effects were found. For this reason, all observers went through a training period in which practice trials of the no-distracter conditions were done. The observers were shown their average RT and number of errors after every 110 trial session. Data on performance during this period were recorded for three observers. These data are plotted in Fig. A1 as the average RT for each day of testing. Data for the no-distracter condition obtained during the main experiments are also shown. Observer A started with the main experiments on Day 3 after 11 practice runs (of 110 trials each). Observer C started on Day 3 after 17 practice runs, and Observer E started on Day 4 after 15 practice runs.

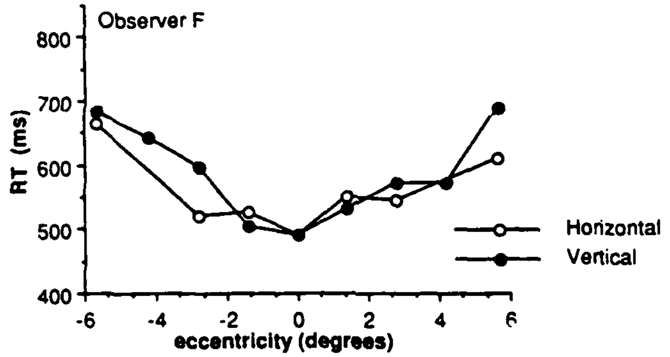
Figure A1 also shows the magnitude of the day-to-day variations in RT. In this paper we expressed performance as the difference between the RT *with* distracter(s) and the RT *without* distracter to factor out some of this variability.



APPENDIX B: EFFECT OF ECCENTRICITY

For eccentricities less than 20 deg, performance on a variety of visual threshold tasks varies approximately linearly with eccentricity (Weymouth, 1958; Anstis, 1974) when this performance is measured with visual acuity. How does performance depend on eccentricity if the task is above threshold, and RTs are measured? An increase in RT with increasing eccentricity was found by Lefton and Haber (1974), using a same/different task with small characters on the horizontal axis. In our experiment the task was identification (not a same/different discrimination) and our elements were twice the size of those used by Lefton and Haber, so we decided to study the effect of eccentricity on RT ourselves, using both the horizontal and the vertical axes. The results for two observers are given in Fig. A2. Both observers show an increase in RT with increasing eccentricity. For Observer F, this increase begins at small eccentricities and continues almost linearly whereas for Observer D, the RTs are essentially independent of eccentricity at small eccentricities, but increase sharply beyond about 4 deg eccentricity. For small eccentricities, we found no significant effect of radial anisotropy: the vertical and horizontal RTs were the same. In these experiments, RT for the most eccentric location in the upper visual field (6 deg vertical) was elevated because of its nearness to the edge of the display. This problem was avoided in the experiments reported in the body of this report by placing the fixation cross below the center of the display. For the most eccentric horizontal





target positions, there was a difference between the left and the right (of the observer); target presentation to the right of the fixation point (shown as a negative eccentricity in the graphs) resulted in a lower RT than target presentation to the left of the fixation point. This agrees with the data of Perry *et al.* (1984) on the distribution of ganglion cell density across the retina: at a given retinal eccentricity, ganglion cell densities are several times greater along the nasal horizontal meridian than along the other three meridians.